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Power boosting for railway power systems with flywheel energy storage system

Master of Science Thesis

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Abstract

The concept of energy storage is emerging as a solution to energy management, energy savings and performance improvement for power systems. From different technologies available, Flywheel Energy Storage Systems (FESS) are gaining importance because of high energy density, large number of discharge cycles, long lifetime, future potential advances and reduced costs for few minutes discharge time.

In this thesis to integrate FESS in the railway power systems as a solution to overcome line voltage drop and irregular peak power loads is motivated by an economic evaluation of the installation. Three different cases are studied in order to retrofit to current Swedish network with the aiming of: improving energy transmission by delivering power on time between two traction stations; absorbing regenerative braking energy and delivering it when a train is moving from a valley to uphill; and reducing the peak power requested in current traction stations.

Keywords: Flywheel, Energy Storage, Railway Power System, Energy Management.

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List of abbreviations

AC	Alternating Current
AVR	Automatic Voltage Regulators
DC	Direct Current
ESS	Energy Storage System
FESS	Flywheel Energy Storage System
GFRE	Graphite Fibre Reinforced Epoxy
NiCd	Nickel Cadmium
Pb-Acid	Lead-Acid
PMSM	Permanent Magnet Synchronous Motor
SOC	State Of Discharge
SRM	Synchronous Reluctance Motor
UPS	Uninterruptible Power Supply

TABLE OF CONTENTS

1- Introduction

1.1 Context

The high power of modern locomotives/trains and the abundant arrival/departure frequency in the key stations cause frequent voltage drops of the local network and limited acceleration capability. Power capacity the traction stations must provide to the overhead line is quite irregular and converters in such stations are dimensioned to deliver much more than the average power needed. Energy storage systems can be a solution to deliver power just on time; buffering temporal variations of loads and sources, giving flexibility and less dependency on the public grid and converters in traction stations.

Flywheel Energy Storage System (FESS) has advantages of high power density, high number of discharging cycles, long lifetime and relatively low costs. The charging of the FESS can be started just a few minutes before the train comes, for instance, and totally discharged during the train acceleration. In the same way, supplying power between two traction stations can reduce the line losses and reduce the voltage drop in the transmission. Given that nearly all electricity in the world is produced from generators and about 65% of the world’s power is used in motors, it makes sense to look at rotational energy storage.

The power of trains and locomotives studied is in between 1.5 to 6 MW. Considering that the discharge time of an energy storage system should be in between 1 to 10 minutes, the energy storage of FESS should be in between 25 to 1000 kWh.

This study is relevant because it shows how FEES can be integrated in the railway power system by increasing overhead line voltage when a train is moving far from any traction station, by taking advantage of regenerative braking to charge it and supplying energy close to the loads, and by reducing the peak power requested in traction stations. Moreover, the integration of FESS in railways power systems for metro/underground and tramway has been successful during the last years; the aiming of this study is to scale the technology to larger power systems.

1.2 Background

Due to the uncertain future state of energy resources and present concerns for environmental conservation; energy saving actions have achieved significant interest for many electrified applications, especially on public transport systems. Energy storage devices can be very helpful to solve the problem of energy management for electric vehicles and its power systems.

The electric consumption in rail electric substations is characterised by the existence of high peaks in some traffic conditions, both for trains, tramways or metro. This has been conducting to the oversizing of some specific equipment such transformers, power converters, protection devices etc.., and in some cases to possible penalties of the supplying electric companies due to the over dimension that feeds the rail system. In figure 1, the power requested (y-axis) in one traction station for trains during one normal day (x-axis) is presented with a blue line; the red line shows the 11.6 MVA available in the converters, i.e. the capacity that the converters in such station can provide in normal operation.

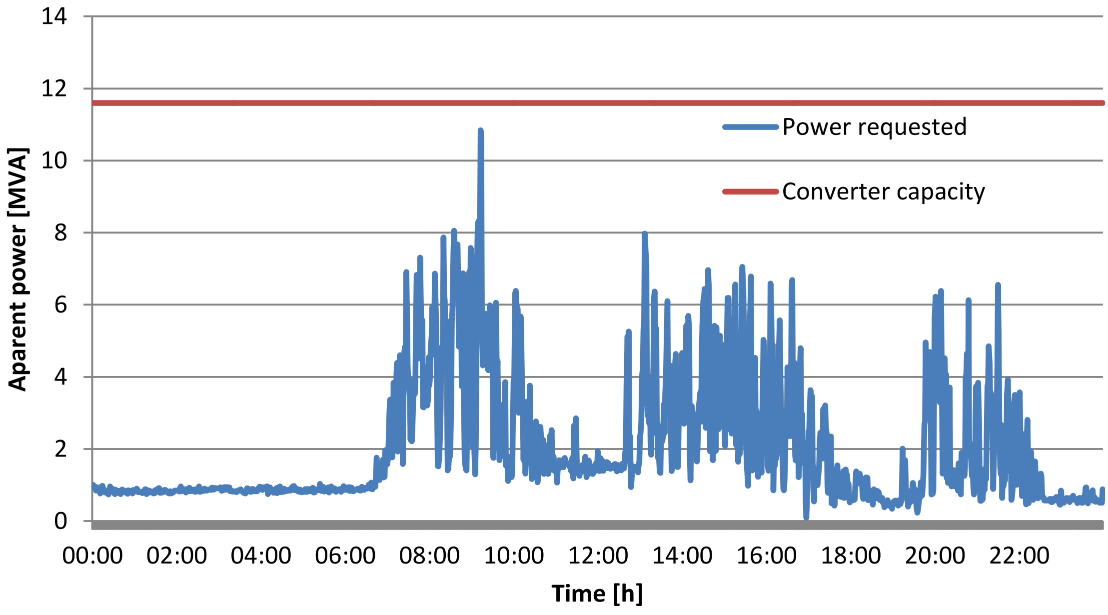

Figure 1 Example of a traction station over dimensioned due to the presence of power peaks [1]

The example is obtained from a small traction station for passenger and freight trains in Sweden. However, this phenomenon appears in all different types of railway power system as commented before. The reason is due to the difficulty of predicting the behaviour of loads moving both in time and space and caused as a consequence of this variable energy demand.

Voltage drop on the overhead line is another typical problem that appears when the train is moving far from the traction stations, especially for weak lines or when the traction stations are quite far from each other. In figure 2 it is shown the voltage drop depending on the distance from the traction stations, the y-axis represents the voltage at the train when it is moving from a traction station (0 to 60 Km in the x-axis). In this example one stations is placed 60km from the other, in the middle the voltage drop is maximum:

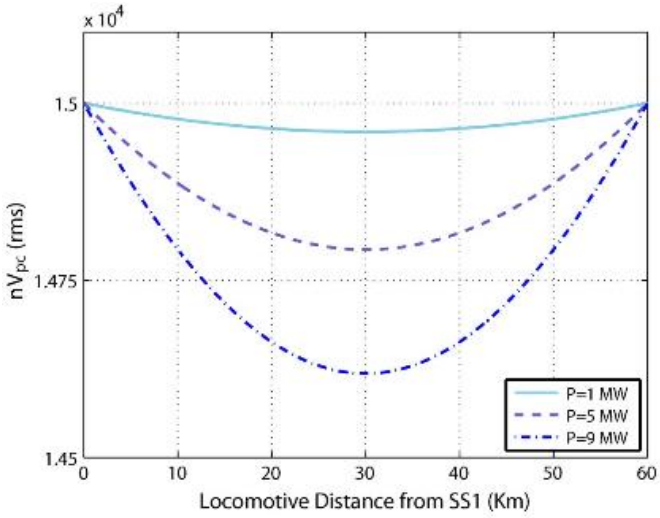

Figure 2 Voltage drop depending on the train load in a 15kV power system. [2]

As a clarification, a traction station is any passenger station with the converters, motors and infrastructure to provide power to the overhead lines in order to supply trains. The distance between two traction stations can vary from 10 to 100 Km depending on the frequency of trains moving in that lines. So, in between two traction station it can be from 1 to 10 passenger station without any supply system.

To face these usual problems, the concept of energy storage in railway power systems for passenger and freight trains is a resource to look into. Loads are moving, varying its power requested along the travel due to geographic changes; energy storage systems will improve the management of large scale power system where preventing patterns of power requested for the system is tough.

Once the problems or needs are identified, a short introduction to energy storage in railway systems is presented below. From this, it will be seen the gap for the present research.

A study [3] presents the current application of energy storage devices in electrified railways as batteries, flywheels, electric double layer capacitors and hybrid energy storage devices. In the article is compared some real installations of energy storage for railways using the Ragone plot. The effect of the use of energy storage devices on electrified railways of the future is discussed as well. The author claims that there is no specific reports on the failures of energy storage devices since most of the applications only show their advantages. Performance improvements or energy savings should come with a financial analysis since this is one of the factors which will encourage the authorities/companies to use energy storage devices. At the same time, manufactures describe their advantages, but no details of any control strategies or operational techniques are shown.

In [4] the authors suggested a superconducting flywheel energy storage application used on Daejeon Metro system with 7 substation and 22 station to reduce peak power and energy savings. Over different scenarios, it is verified that the flywheel can contribute to the reduction of operating cost. The peak power is reduced by 36.7%, 3375 kW, and the total amount of energy saving is near 48 MWh. Its financial improvement reaches about 24000 dollars per month.

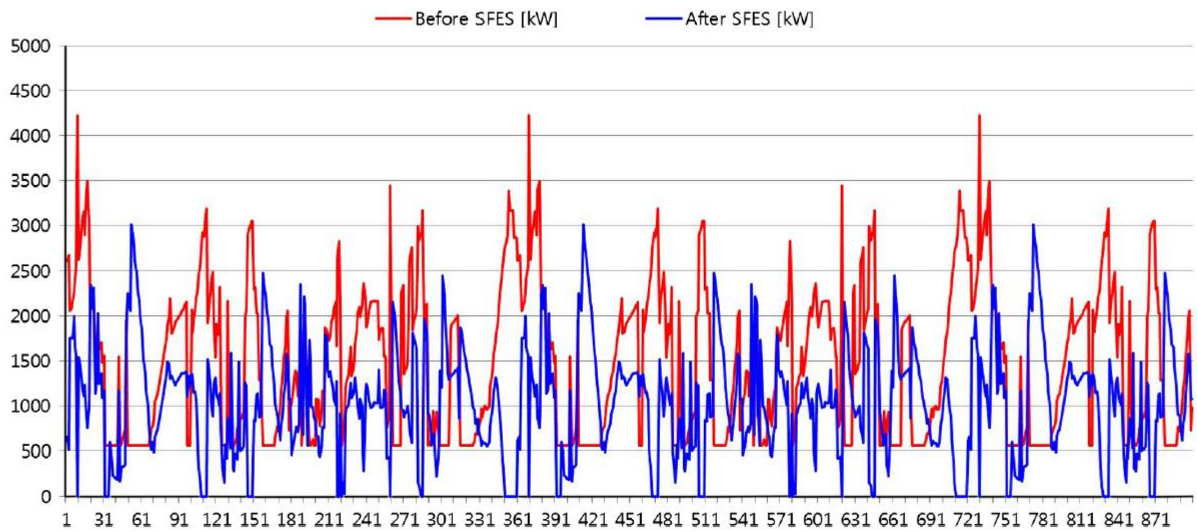

Figure 3 Peak power before and after adding the Superconducting Flywheel (SFES) [4]

Despite the calculations on cost are not detailed, the financials gaining are very interesting. A closer and more detailed look in the costs will be studied in this thesis.

In [5] the author look into larger railway power systems and discuss the potential gaining on performance and cost reduction when installing a wayside energy storage system for different energy capacities. The article was written in 1984 were FESS were not technically nor economically comparable with Pb-Acid batteries. In figure 4, the peak reduction by installing an Energy Storage System of 0.1 MWh and 1MWh energy capacity show how the peak reduction is achieved. The conclusion of that article argues that the reduced energy supply cost did not justify the costs of installing any Energy Storage Systems; however that conclusion might be changed if the installation was remote from the nearest utility, when considerations of stability or costs of supply might alter the balance of costs and savings.

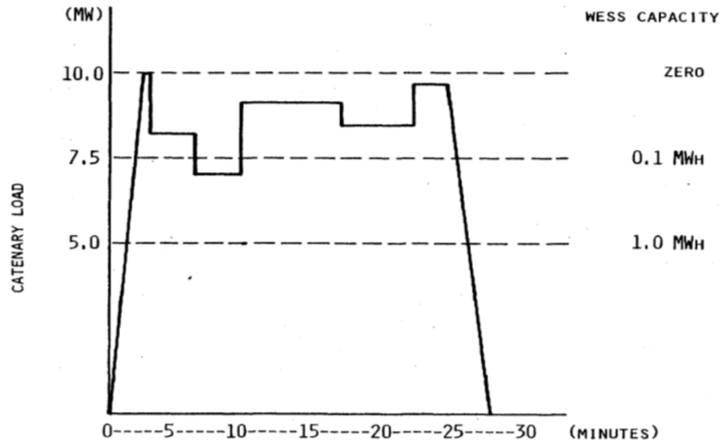

Figure 4 Peak power reduction for different energy capacities [5]

Once the current literature has been studied, it is easy to raise the gap, the need for the present research. The following list of points defines it:

- Most of the articles focus in railway power systems for tramways or metro, lacking a deep study on energy management for passenger and freight trains.
- Flywheel technology has evolved considerably in the past years; however there are no studies that match the current technologies with the improvements that can provide to large power systems.

In this study, how to incorporate flywheels as an energy storage system in railway power systems for trains will be studied.

1.3 Purpose

The aim of this project is to use the depth knowledge on flywheels and its advantages in front other technologies to prove how they can enhance the power system performance and achieve energy saving in some railway application, emphasizing the application of this energy storage system for passenger and freight trains. Quantify the increase of the power quality in the railway power system and the cost advantage by incorporating FEES will be the point of research, investigated on real case scenarios. Simulations of the power system for a specific power, energy and depth of discharge will be carried out to motivate how this study can be useful for railway companies in order to retrofit its network. Furthermore some efforts will be done to tie real demands with already manufactured flywheels, with the aiming of matching theoretical calculations and physical implementations. Different scenarios on how to integrate FESS in the Swedish railway power systems with the economic and technical aspects is discussed in this thesis. Investment will be compensated by a reduction of the energy consumption and less peak load demand tariff from the supplier, at the same time can be an alternative when a traction station needs more power and it cannot be provided from the energy dealer or when the converters in traction stations needs a maintenance service.

Summarizing, this master thesis will bring on flywheels as an energy storage system to support the railway power system for passenger and freight trains. Energy saving and financial calculation are included.

1.3.1 Research objectives

1- Integrate FESS in order to improve energy transmission:
   This solution is an alternative to increase the section of the power lines when more power is required to reach better performance. The aiming of FESS is delivering the power on time between two traction station, reducing voltage drop and line losses.

2- Integrate FESS to current traction station in order to reduce the peak power requested:
   This solution is an alternative to not over dimension the power supply converters using FESS to reduce the ratio Peak Power over Average Power.

1.4 Scope

The study focuses on railway application as a major study, hence the specifications for the flywheel will move in those numbers that better fit the railway applications. In addition, the thesis considers power systems for trains, neither tramways nor subways/metro where the range of power and energy is less.

In order to avoid sizing and weight issues, this thesis will focus on wayside flywheels instead of on board implementation. The present research is not including hybrid systems, i.e. the combination of more than one technology. The author considers that the first step is to make a study for flywheels and further on, as a future research, discuss how other technologies can complement flywheels and make the system even better.

Due to limitations in simulation tools, the railway power system is modelled in a simple way; however, three different scenarios have been considered in order to justify the feasibility of FESS.

1.5 Method

Information has been gathered from Trafikverket, books and internet, scientific articles and magazines have been found in databases, such as IEEE or Chalmers library. To get specific information about different components, the manufacturers will be contacted through e-mail and telephone.

The first step will be to compare flywheels and other energy storage technologies for railway applications. Then, a deep research on the theory behind the flywheels will be done: used material, limitations on performance, description of the internal components, prototypes developed, and current manufacturers. In order to identify the application and fix specifications a research on already made installations using flywheels in railway power systems will be carried out.

After that, a study of the railway power systems in Sweden will be presented; defining the electric machines, converters, line properties that will be used to model the power system and define the appropriate mathematic model used to carry out calculations in MATLAB.

The economic aspects on how much the company affected gains by reducing the peak power requested, increasing the performance of the system, and achieving energy savings will be the motivation to see if it is feasible to retrofit the current installation.

Regular meetings with experts in Trafikverket will be appointed with the intention to know and understand the problems in the railway power system in Sweden.

2- Theory and literature review

This section is offering an overview of significant literature published that it is relevant for a complete understanding of this thesis:

In the first subsection a comparison between different energy storage systems for explicit requirements is shown, the aiming is to see if flywheels are a good technology to be used in railway power systems and if they are competitive with other mature technologies as Lead-Acid batteries. From there, the reader will be able to identify the strong and weak points for each technology. Moreover, a calculation of the cost for each technology is made based on power and energy density data.

The second subsection introduces which are the parameters that have major relevance when calculating the energy stored in a rotating mass. Furthermore a differentiation of energy stored and energy density stored is explained.

Linked to the previous one, the third subsection shows an economic and performance comparison between the two most common materials that flywheels are made, steel and graphite fibre reinforced epoxy.

The forth subsection summarize the history of flywheels in terms of dimension, mass, material and speed when designing the rotating mass in order to see the trend of the past years.

In the fifth subsection, some figures shows the internal layout of a flywheel assembly, with a special emphasis on the motor/generator commonly used and the reason behind it.

To match this thesis with other flywheel designs, the sixth subsection displays a list of the flywheels researched and subsequently their prototype design used in railway applications. Most of them are not manufactured and the design finished on the prototype, however, some of them are implemented and used nowadays.

In order to be closer to reality, a list of the main suppliers of flywheels and some of their properties are displayed in subsection seven.

Finally, in the eighth subsection an introduction to the Swedish railway power system is given in order to introduce the chapter number three, problem definition.

2.1 Energy storage system comparison

There are several types of energy storage devices used in power systems, their application depend on the advantages they can provide. The aiming of this section is to compare flywheels with other technologies in an extensive classification. Since this study is targeting to incorporate/retrofit the railway power system with an energy storage system close to the loads, compressed air, superconducting magnetic and pumped hydro technologies are ruled out from the comparison since these are strongly dependant on the geographical situation. A list of technologies suitable for energy storage in the railway application is represented below:

- Flywheels
- Lithium-Ion batteries
- Lead-Acid batteries
- Nickel-cadmium batteries
- Supercapacitors

The specific application of this study will restrict the usage of some: Since the main interest is to supply energy as close as possible to the train, and this one is moving, the depth of discharge must be short, less than 10 minutes (based on acceleration and braking times). In figure 5 it is shown a comparison of the Energy density and Power density of different technologies and the red lines represent the relation Energy/Power which is time by definition:

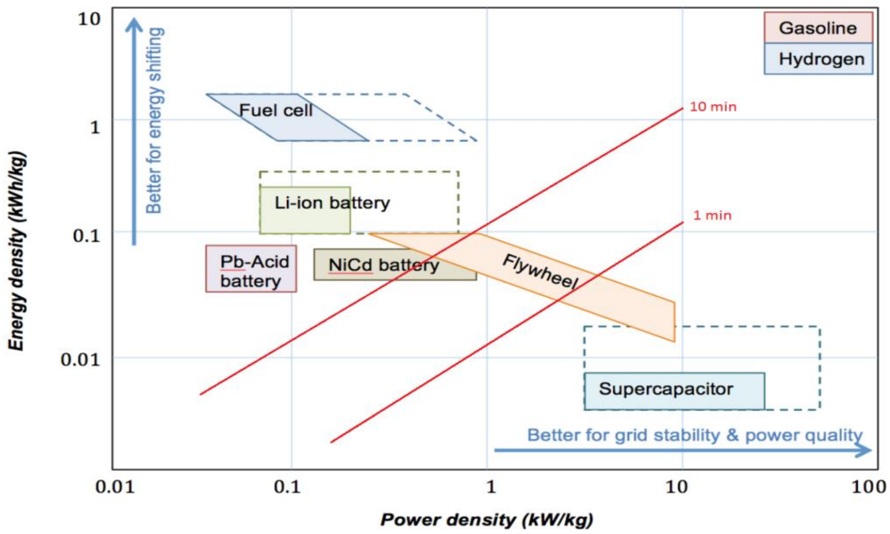

Figure 5 Performance of different energy storage technologies [6]

In the calculations of power density only the net energy mass is considered. The structural construction and parts are not included. The dashed line indicates the future developments of the corresponding technology. What this figure shows is which technology is best dimensioned for a discharge time between 1 and 10 minutes, which places flywheel in the best position. The previous graph is known as *Ragone plot*, used when comparing energy storage technologies.

For the following calculations, values of energy density and power density are obtained from the graph, taking the best-case for each technology.

For a 10 minutes discharge, 0.167 kWh/kW technologies such as Li-ion battery, NiCd battery or flywheels don't need to be oversized. For each kg, the relation power/energy is the one that provides 10 minutes discharge cycle. However the Pb-Acid battery must be oversized to meet the power requirements and supercapacitors must be oversized to meet energy requirements. The best-case is 3 times heavier for a Pb-Acid and 25 times heavier for Supercapacitors, as it can be seen in table 1.

Table 1 Energy and power density for different technologies in a 10 minutes discharge time target

	Energy density (KWh/Kg)	Power density (KW/Kg)	Discharge time (h)	Target (h)	Oversizing rate
Supercapacitor	0.02	3	0.0067	0.1670	25
Pb-Acid battery	0.05	0.1	0.5	0.1670	3

Similarly, for a 1 minute discharge, Pb-Acid must be 30 times heavier, Li-ion 8.6 times, Ni-Cd 3.5 times to meet power requirements and 2.5 for supercapacitors to meet energy requirements

Table 2 Energy and power density for different technologies in a 1 minute discharge time target

	Energy density (KWh/Kg)	Power density (KW/Kg)	Discharge time (h)	Target (h)	Oversizing rate
Supercapacitor	0.02	3	0.0067	0.0167	2.5
Pb-Acid battery	0.05	0,1	0.5000	0.0167	30
NiCd battery	0.06	1	0.0600	0.0167	3.5
Li-ion battery	0.1	0,7	0.1429	0.0167	8.6

Over dimension, which means more weight, is not a problem in the application of this study, however the previous calculations have a major impact when calculating the cost associated to each technology, since most of them have to be oversized to meet power and energy requirements. In the following figure the cost for kW (Power) and kWh (Energy) for different technologies is displayed. The dashed line indicates the estimated installation cost for wind power and solar panels

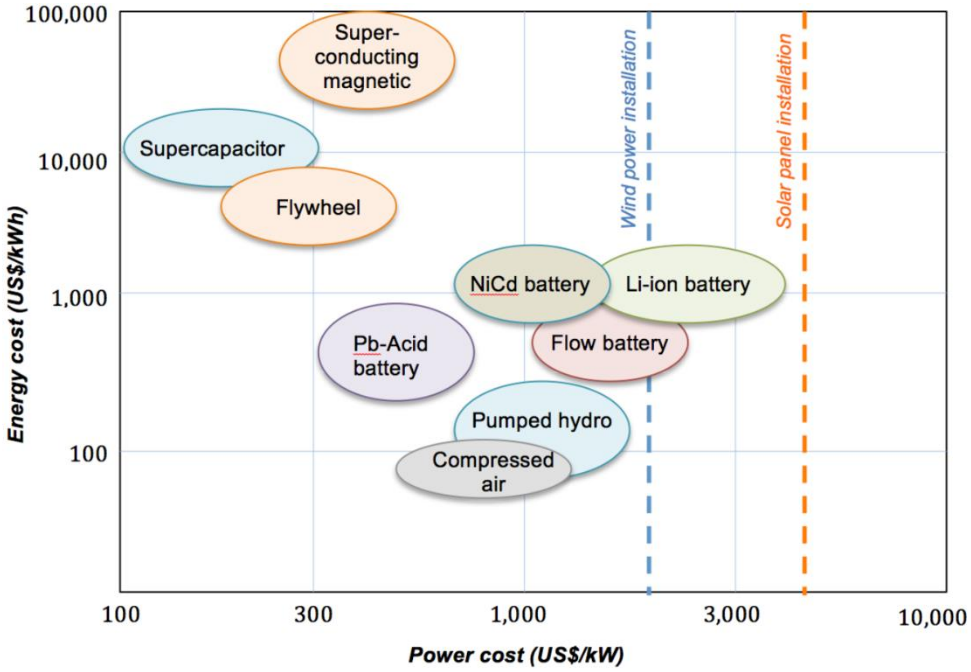

Figure 6 Costs of different energy storage technologies [6]

Technologies with low energy cost and low power are desired. However, each technology has a relation of power and energy per kg as seen in figure 5. Thus, fixing the power capacity, a rough idea of the associated cost can be found.

From the graph is obtained an average energy cost and power cost represented in table 3:

Table 3 Average energy cost and power cost for different technologies

	Energy cost (US$/KWh)	Power cost(US$/KW)
Supercapacitor	10000	200
Flywheel	4000	300
Pb-Acid battery	500	500
NiCd battery	1000	1000
Li-ion battery	1000	2200

From table 3 the values must be adjusted to match the application of this study. For a 10 minutes discharge, Pb-Acid will have an excess of energy 3 times the requested to meet power requirements, then the energy cost it is 3 times more expensive. Similarly the adjusted power cost for supercapacitors will be 25 times bigger since to meet the energy requirements it will have an excess of power. Adjusted values are represented in bold type in table 4. The corrected cost for a ten minutes discharge (0.167h) is calculated as below. The reason why the cost is calculated over KW is because it is the unit used for flywheel suppliers:

$$Corrected\ cost\ \frac{US\$}{KW} = Energy\ cost\ \left(\frac{US\$}{KWh}\right) \cdot 0.167(h) + \text{Powecost}\left(\frac{US\$}{KW}\right) \text{ [Eq. 1]}$$

Table 4 Adjusted average energy cost and power cost for a 10 minutes discharge

	Energy cost (US$/KWh)	Power cost(US$/KW)	Corrected cost(US$/KW)
Supercapacitor	10000	**5000**	6670
Flywheel	4000	300	968
Pb-Acid battery	**1500**	500	750,5
NiCd battery	1000	1000	1167
Li-ion battery	1000	2200	2367

In the same way, for one minute discharge (0.0167h) the adjusted values are represented in red in table 5 and the corrected cost is shown in equation 2:

$$Corrected\ cost\ \frac{US\$}{KW} = Energy\ cost\ \left(\frac{US\$}{KWh}\right) \cdot 0.0167(h) + \text{Powecost}\left(\frac{US\$}{KW}\right) \text{[Eq. 2]}$$

Table 5 Adjusted average energy cost and power cost for a 1 minutes discharge

	Energy cost (US$/KWh)	Power cost(US$/KW)	Corrected cost(US$/KW)
Supercapacitor	10000	**500**	660
Flywheel	4000	300	364
Pb-Acid battery	**15000**	500	740
NiCd battery	**3500**	1000	1056
Li-ion battery	**10000**	2200	2360

These numbers give just an approximation of reality. Detailed information depends on manufacturing processes, number of units built, installation costs... Nevertheless, the previous calculations show that Lead-Acid batteries are the cheapest technology for a 10 minutes discharge, and flywheels the second one. For a 1 minute discharge flywheels are the cheapest with big difference, being supercapacitors the second one. The trend is showing that flywheels have the cheapest corrected cost in a range from 1 to 10 minutes; it has sense to look into flywheels in terms of technology cost.

In order to place FESS in a better position than Lead-Acid battery or super-capacitors, other operation features must be raised: FESS present stable voltage and power level independent of the depth of discharge, state of charge and temperature for a longer life cycle compared with their competitors. To know the energy stored it is only needed the rotational speed of the rotating mass, while energy stored by batteries and super-capacitors are more difficult to predict. Power electronics are the responsible to set the limitation on the output and input power of the motor/generator responsible to spin the flywheel, while electrochemistry is the limiting factor for batteries and supercapacitors. The trend shows a future advances in the control of the motors and an increase of power density will be seen in the following years [7].

As discussed in [8] , other considerations must be taken as:

- Technical maturity
- Public acceptability
- Environmental impact
- Future potential advances

A Pugh matrix, which is an evaluation method to compare the previous considerations, is showed in table 6

Table 6 Pugh matrix with overall score for different considerations

Good = 5 **Poor = 0**	**Technical maturity**	**Public acceptability**	**Environmental impact**	**Future potential advances**	**Overall score**
Supercapacitor	2	5	3	2	12
Flywheel	2	5	4	3	14
Pb-Acid battery	5	1	0	1	7
NiCd battery	3	3	0	1	7
Li-ion battery	2	4	2	3	11

Flywheels show good results in these considerations, followed by supercapacitors and Li-ion batteries. It is as well important begin able to "score" good results in the previous table, showing that not only the economical approach matters, but the social and environmental. Sustainability, term that combines a good economic, social and environmental approach is one reason to invest on flywheels.

2.2 Flywheel energy storage theory

A flywheel is a rotating mechanical device that is used to store rotational energy spinning on its axis of revolution. Energy contained in a flywheel is defined by the equation 3.

$$E = \frac{1}{2} \cdot I_c \cdot \omega^2 \quad \text{[Eq.3]}$$

Where I_c is the moment of inertia and ω the angular velocity of the flywheel. The moment of inertia I_c is defined for the axis of rotation and it depends on the shape and mass of the device. In the figure 5 it is shown the value of the moment of inertia I_c of the two typical configurations of flywheel.

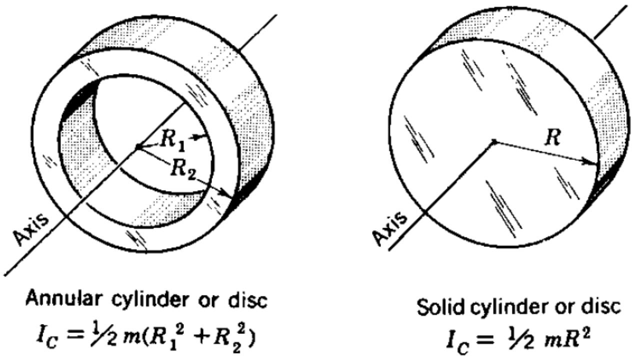

Figure 7 Moment of inertia for simple configurations [9]

The energy stored for the two previous configurations is represented in the equations 4 and 5:

$$E_{AnnularCylinder} = \frac{1}{4} \cdot \mathrm{m} \cdot (\mathrm{R_1}^2 + \mathrm{R_2}^2) \cdot \omega^2 \quad \text{[Eq. 4]}$$

$$E_{SolidCylinder} = \frac{1}{4} \cdot \mathrm{m} \cdot \mathrm{R}^2 \cdot \omega^2 \quad \text{[Eq.5]}$$

In both cases energy stored is proportional to the square of rotational speed and radius; mass influence is just proportional. As far the mass is from the axis of rotation a bigger inertia, more energy will be contained in the device. Comparing the two configurations showed above; the annular cylinder will have a bigger inertia for the same mass than the solid cylinder if the outer radiuses are the same. As faster the flywheel is spinning more centrifuge force will be applied into the outer surface, according the second Newton's law. The maximum stress the flywheel can handle, defined as the maximum force divided by the area where this force is applied is dependent on the material the flywheel is made.

Increasing the speed or the moment of inertia, by using more mass or a larger radius, increases stored energy. However, the amount of energy that can safely be stored in the rotor depends on the point at which the rotor will warp or shatter. The hoop stress on the rotor is a major consideration in the design of a flywheel energy storage system. The literature [10] provide the maximum tangential and radial stresses r resultant from the rotation of a ring with and outside radius = r_2 and inside radius = r_1 spinning at an angular velocity ω. These formulas can be used for the annular cylinder or the solid cylinder.

$$\sigma_{t\,max} = \rho \cdot \frac{\omega^2}{4}((1-\nu)\cdot r_1^2 + (3+\nu)\cdot r_2^2) \text{ [Eq. 6]}$$

$$\sigma_{r\,max} = \rho \cdot \frac{\omega^2}{8}(3+\nu)\cdot (r_2 - r_1)^2 \text{ [Eq. 7]}$$

When designing the flywheel the value of $\sigma_{t\,max}$ and $\sigma_{r\,max}$ must not overpass the value defined for each material. $\sigma_{t\,max}$ will be higher than $\sigma_{r\,max}$ for all range of values so the tangential stress will be considered as a limitation on the design.

Furthermore, if the flywheel is spinning under low levels of pressures the maximum stresses will be lower.

Making $\sigma_{t\,max} = \sigma_{admisible}$ the maximum energy stored can be related to the shape and the material used. Some articles focus on the energy density stored as a major issue when designing and choosing material for the flywheel, in the following lines will be presented the maximum energy density and the maximum energy stored for the two types of configuration.

$$\frac{E_{AnnularCylinder}}{m} = \frac{\sigma_t \cdot ({r_1}^2 + {r_2}^2)}{\rho\cdot((1-\nu)\cdot r_1^2 + (3+\nu)\cdot r_2^2)} \quad \text{[Eq. 8]}$$

$$E_{AnnularCylinder} = \frac{\sigma_t \cdot ({r_1}^2 + {r_2}^2)}{((1-\nu)\cdot r_1^2 + (3+\nu)\cdot r_2^2)} \cdot \pi \cdot ({r_2}^2 - {r_1}^2)\cdot h \quad \text{[Eq. 9]}$$

$$\frac{E_{SolidCylinder}}{m} = \frac{\sigma_t}{\rho\cdot(3+\nu)} \quad \text{[Eq. 10]}$$

$$E_{SolidCylinder} = \frac{\sigma_t}{(3+\nu)} \pi \cdot {r_2}^2 \cdot h \quad \text{[Eq. 11]}$$

When comparing flywheels whit the same shape but different material, those with a ratio $\frac{\sigma_t}{\rho}$ bigger will have the large energy density. This parameter is especially important when mass of the flywheel is an issue. As it will be explained later high strength composites have this parameter bigger than steel but on the other hand steel is much cheaper. The compromise between this factor and the application where the flywheel should be used will decide which material is more suitable.

2.3 Steel vs. high strength composites

Steel and graphite fibre reinforced epoxy (GFRE) are the most common materials used when manufacturing flywheels. In this section an economical and technical comparison according the two configurations studied previously is explained:

Material density for steel moves around 7780 Kg/m^3, however for GFRE density is strongly dependant on the percentage of the components. 1500 Kg/m^3 would be the density of a composite with a ratio of 60-70% carbon fibre over epoxy. [11]

In this study it is considered 1300 MPa as material strength for steel with a cost of 2.20 US $/Kg. For GFRE material strength is dependent on the manufacturing method, properties of the fibres and the ratio of epoxy that the composite material contains among others. To find a good compromise between the cost of the fibres and the strength of them, it is identified a 5500 MPa at the expense of 110 US $ /Kg. The final strength is dependent on the ratio fibre over epoxy, keeping the same ratio as the density; the final net strength is around 3500 MPa for the composite.

To continue evaluating the material, a thick-wall cylinder is built with these dimensions:

- Outer diameter: 0.3 m
- Inner diameter: 0.15 m
- Height: 0.4 m

Table 7 show the comparison in performance and cost for the two types of material selected. Material density and material strength have been discussed in the previous paragraph. Poisson ratio is used to determine the stored energy and maximum rotational speed in the breaking point. Weight gives an idea of the cost of the flywheel.

Table 7 Comparison of a steel and GFRE flywheel

Material	Material density (Kg/m3)	Material strength (MPa)	Poisson ratio	Material cost (US$/Kg)	Weight (Kg)	Angular velocity to break (RPM)	Stored Energy to break (MJ)	Flywheel cost (US$)
Steel	7780	1300	0,27	2,2	660	14005	40	1452
GFRE	1500	3500	0,3	110	127	52166	173	13996

Conclusions:

The result shows a 9.5 times more expensive GFRE flywheel. On the other hand, steel flywheel can store 4.3 times less energy and weights 5.2 times more. Attention must be made on Energy to break number since, as discussed in the previous section this is the one to look into for flywheels where mass is not a relevant parameter.

If weigh or space is a critical parameter in the design of a flywheel (for example, the ones developed inside cars), GFRE materials is probably the best option, because of the high energy density at the expense of higher costs. But, is it steels a better choice when space or weigh is not a critical parameter, i.e. in wayside energy storage systems like the ones studied in this thesis?

Actually, weight is always an issue when designing flywheels, as heavier the flywheel is, more powerful the bearings should be, and more complex the stability control is. Now, two question show up:

- How the increase of weight affects the bearings spinning at high speed?
- How the history of flywheels has evolved?

The first question is beyond the scope of this project, since the cost of bearings depends on the weight of the rotor and the speed it is spinning. At the end, the correct approach in order to see the influence of the increase of rotor's mass against magnetic bearing characteristics is to see what the cheapest solution is. However, no studies shows that the increase of cost for light weight material to be rotors worth the decrease of cost in magnetic bearings that have to handle less loads but this is what history of flywheels says. It will be discussed in the following section.

2.4 The three generations of flywheels

As shown in the previous section, there are 3 main parameters to consider when designing a flywheel to storage energy: mass, angular speed and shape of the rotor. The appropriate trade-off between these parameters has been a technological and economical challenge. Three generation of flywheels has been identified:

First generation

It is made of conventional materials such as steel and they can weight tens of tons, having low energy storage density. Defined as low speed flywheels they rely on the mass of the rotor to storage energy however with such a heavy structure angular speed is low because of the technology limitations for the bearings.

Second generation

The second generation of flywheels rely on speed as the way to store energy. The big change compared with the first generation is the use of composite materials for the rotor, which together with magnetic bearings allow these devises reaching speeds up to 60.000 rpm in vacuum enclosure, with minimal drag resistance, reaching higher efficiencies. Since weight is reduced, the capacity of store energy in less time is achieved, increasing the power density of the previous generation [12]. Light weight fibre composite materials are used to increase efficiency [13].

Third generation

Recently, the 3rd generation of flywheels is coming up, where the best compromise between mass and speed in order to maximize the energy stored is researched. The assembly consists on a big thin-walled hoops made of composite materials suspended by radial gap magnetic. Great efforts have to be done in the suspension of such a big rotor. [14]

2.5 Internal configuration

In this section, a description of the flywheels assembly is displayed. It consists on a number of components listed below:

- Rotating flywheel which stores kinetic energy.
- Mechanical connection of the flywheel to the rest of the system, including bearings.
- Electrical connection, which converts the rotating energy to electric power (motor/generator)
- Power electronics subsystem, which interfaces with the external electric system, providing the required voltages, currents, frequencies, etc.
- The containment and safety systems.

Different configuration of the rotor-stator can be found as the following ones:

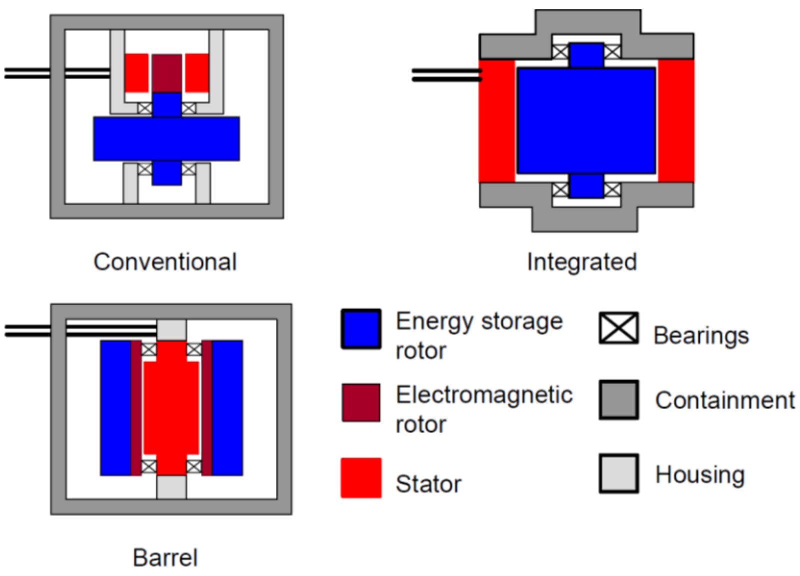

Figure 8 Various flywheel configurations [15]

Some examples of the embedded system, including a typical second generation flywheel, figure 10, and a third generation flywheel, figure 11:

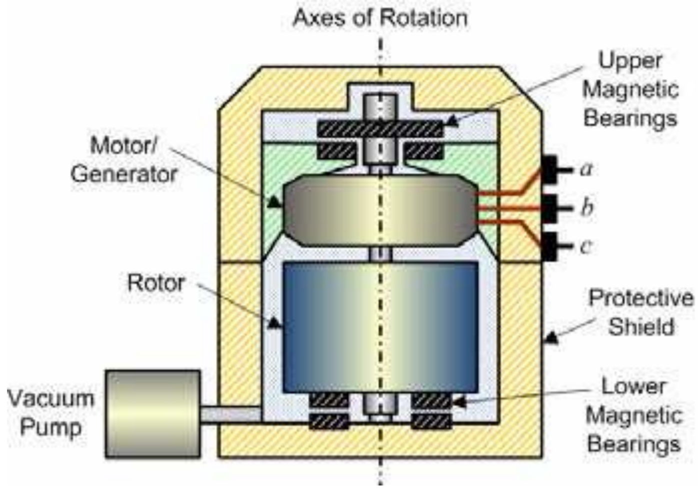

Figure 9 Second generation flywheel with conventional energy storage rotor

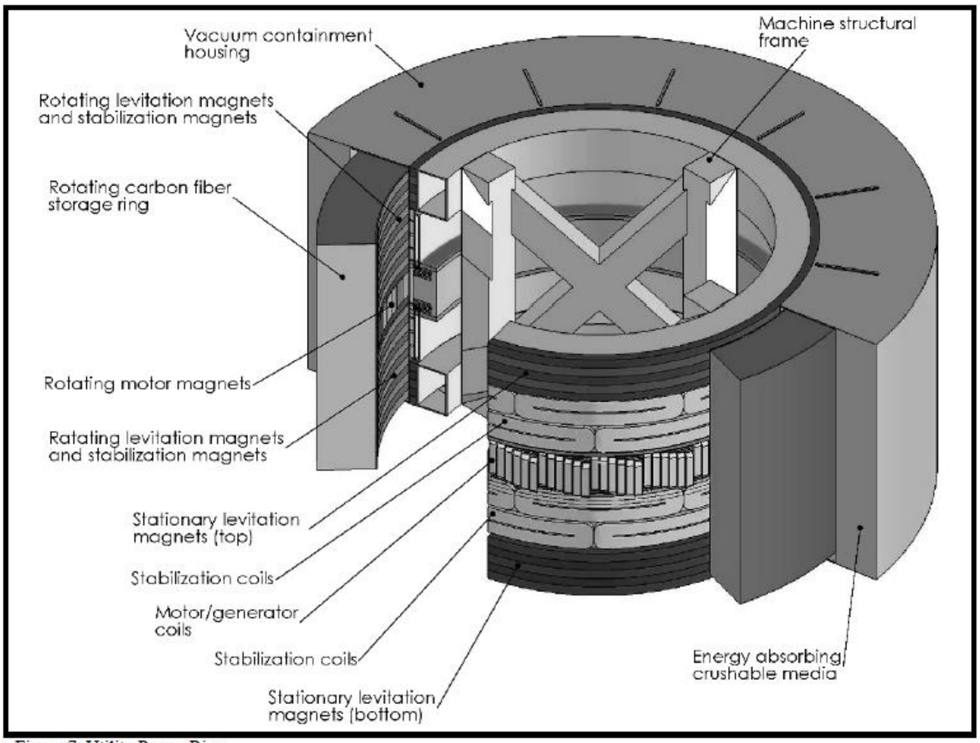

Figure 7. Utility Power Ring

Figure 10 Third generation flywheel with barrel energy storage rotor configuration [14]

Motor/Generator

Flywheels incorporate a Motor/Generator in order to convert the electrical energy into mechanical and vice versa. Looking into the literature and the manufacturers is possible to know which motor/generator is used to power flywheels. The most common used are Permanent Magnet Synchronous and Reluctance Synchronous Motor/Generator [16] [17] [18]. Since loses due to air friction has to be minimized, the flywheel is placed in a vacuum chamber so a rotor producing minimal heating is required, that is why these two types of motor fits this application:

Permanent Magnet Synchronous Motor - Generator

- No electrical energy is absorbed by the field excitation system and thus there are no excitation losses which mean substantial increase in efficiency.
- Higher power density and/or torque density than when using electromagnetic excitation.
- Better dynamic performance than motors with electromagnetic excitation (higher magnetic flux density in the air gap).
- Simplification of construction and maintenance.
- Reduction of prices for some types of machines.

Synchronous Reluctance Motor-Generator

- Variable speed and torque application.
- Without windings or magnets.
- Much lower cost than a Permanent Magnet machine (because there are no magnets)
- Almost 0 rotor losses (higher torque density than Inductive Machine).
- Simple manufacturing process using existing infrastructure.
- Good field weakening capabilities for wide power range.
- No conductors in the motor
- AC sinusoidal machines are capable of delivering smooth output torque.

The future challenges for this Motor/Generator are described below:

- High saliency ratios of 8 or higher are needed to approach performance metrics of well – designed induction machines
- Achieving high saliency ratios typically requires increase of rotor complexity and reduction of its structural integrity.
- Unlikely to be able to challenge key performance metrics of PM machines

Historical success has been limited:

- Previous rotor designs didn't produce sufficient saliency
- Rotor configurations weren't robust enough against forces

A study [19] presents a synchronous reluctance motor/alternator design for a flywheel energy storage system, where the goal of the project is to provide an inexpensive alternative to permanent magnet machines in this application. Key design criteria for the machine are high power output at high speeds with high efficiency and low rotor losses. The proposed rotor design consists of alternating layers of ferromagnetic and non-magnetic steels which are bonded together using a high-strength process such as brazing or explosive bonding. Analytical expressions are developed to calculate the direct and quadrature inductance, as well as maximum output torque and maximum-power-factor torque, of that design. These expressions are then used to design rotors with optimized performance.

Stator and rotor design criteria are developed and combined in the formulation of a design process for high-speed synchronous reluctance machines. Two prototypes machines, designed to provide 60kW over a speed range between 24.000 to 48.000 rpm have been constructed along with two 400V, 240A inverters. A stator-flux-oriented torque controller with an optimal-efficiency algorithm has been developed to drive the machines. Experimental results validated the design process; expect that core losses in the stator iron were significantly higher than expected. Nevertheless, efficiencies of up to 91% were achieved at a 10kW, 10.000rpm operating point with estimated rotor losses less than 0.5% of total input power

On the other hand, the NASA Glenn Research centre [20] gives motivations on why a permanent magnet machine can be used for to power flywheels. Among others their design requirements are high specific power and high efficiency with low rotor losses. This is achieved by the right selection of Motor/Generator configuration, the application of high magnetic energy permanent materials (NdFe group has a high remnant magnetization and energy product), the application of high permeability core lamination material, the selection of an AC permanent magnet synchronous machine with the zero fundamental frequency rotor magnetic and conductive losses and the application of thin diameter stranded wires for the stator armature conductors to reduce the high frequency skin effect losses.

2.6 Implemented flywheels or prototypes

At the University of Texas at Austin, great efforts have been taken to progress in FESS, in such a way that it has become one of the most important places in the United States researching this technology during the past years. Some of achievements are listed in Figure 11, where a comparison of rated power and discharge time for various storage technologies can be seen. According to their studies flywheels are considered to be pulse power devices that compete well with supercapacitors or high power lithium ion batteries. However, CEM has also developed flywheels which can provide longer term energy storage needs, being on special interest for this thesis. The first example is shown as item number 3, which was a 130 kWh flywheel, 2MW motor-generator to provide energy storage for an advanced hybrid locomotive train. [21]

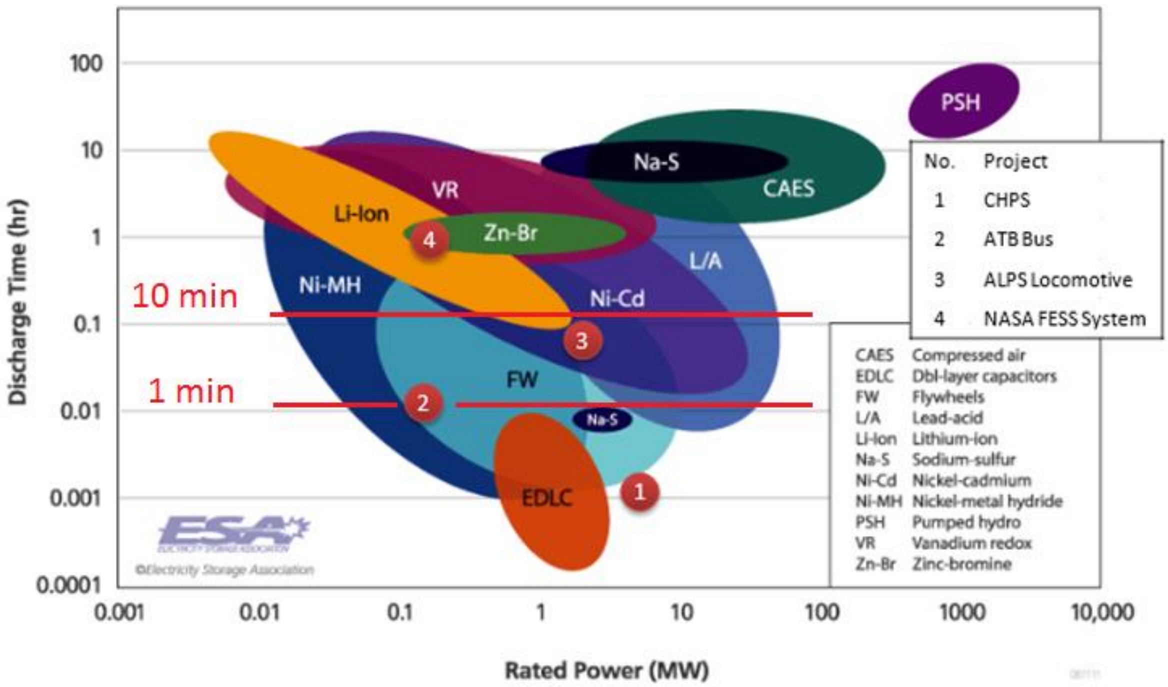

Figure 11 Comparison of energy storage technologies and CEM flywheels [21]

In this application, flywheel energy storage system is used for rapid acceleration, speed maintenance on grades, and recovery of braking energy. A study of the spin commissioning and drop tests for this flywheel is done at [22]. However, no physical implementation has been found.

Somewhere around the point number 3, approximately 130kWh 2MW could be of major interest for railway application in trains. Since in the case studied in the thesis the trains will be fully electric, a slightly bigger capacity and discharge time may be required. A single unit or a multiple unit implementation is cost-related decision.

Rated power for passenger and freight trains moves around 1 to 6MW approximately[1] and as explained before the discharge time will be around 1 to 10 minutes. Energy stored in the flywheel is defined as a consequence of fixing the maximum output power and discharge time, values around 100 to 1000 KWh are the expected values for this application.

From different literature, it is shown a list with different FESS, some of them are only found as a prototype and others are currently implemented.

Table 8 Flywheel prototype and flywheel implemented

	Power (kW)	Energy (kWh)	Year (Generation)	Others
Keihin Electric Express Railway at Zushi	2000	25	1988 (First)	Implemented
Launch Point	50.000	5000	2008 (Third)	Prototype
ATZ and MM [2]	250	12.5	Second	Prototype
Kinetic Energy System ACE2	350	56	2003 (Second)	Prototype
Kinetic Energy System SA2VE	5600	889	2006 (Second)	Prototype

In some other places like in London underground, it has been used a 300kW flywheel, with no details on energy, then it upgrades top 1MW. Investment was recovered in 5 years

[1] *Based on data found at www.jarnvag.net*

[2] Adelwitz Technologiezentrum GmbH (ATZ) and Magnet-Motor GmbH (MM)

2.7 Current Suppliers

Simulations, prototypes and studies always differ from reality: In this section a list of the main suppliers of flywheels and its characteristics place the flywheels in the market.

Some research has been done in this field. The main suppliers of flywheels are:

1- Beacon Power
2- Kinetic Traction Systems
3- Pentadyne

Some of the characteristic of their flywheels are:

Table 9 List of suppliers and flywheel characteristics

	Beacon Power	Kinetic Traction Systems	Pentadyne / Power THRU
Flywheel generation	Second	Second	Second
Power (KW)	190	200- 300(When upgrade)	200
Energy (KWh)	12.5	GTR (1.5KWh)	GTX model (0.68kWh) and GTR (1.4kWh)
Max speed (rpm)	15500	25800-37000	N/A
Material	Mix of carbon fibre and fiberglass	Carbon fibre	Carbon fibre
Type of bearings	Magnetic	Magnetic	Magnetic
Motor/Generator	PMSM	PMSM	Synchronous Reluctance
Voltage input	480VAC	570-900VDC	570VDC-900VDC 1,000VDC-1,500VDC

Output power versus time for several available flywheel operating configurations displayed in figure 12:

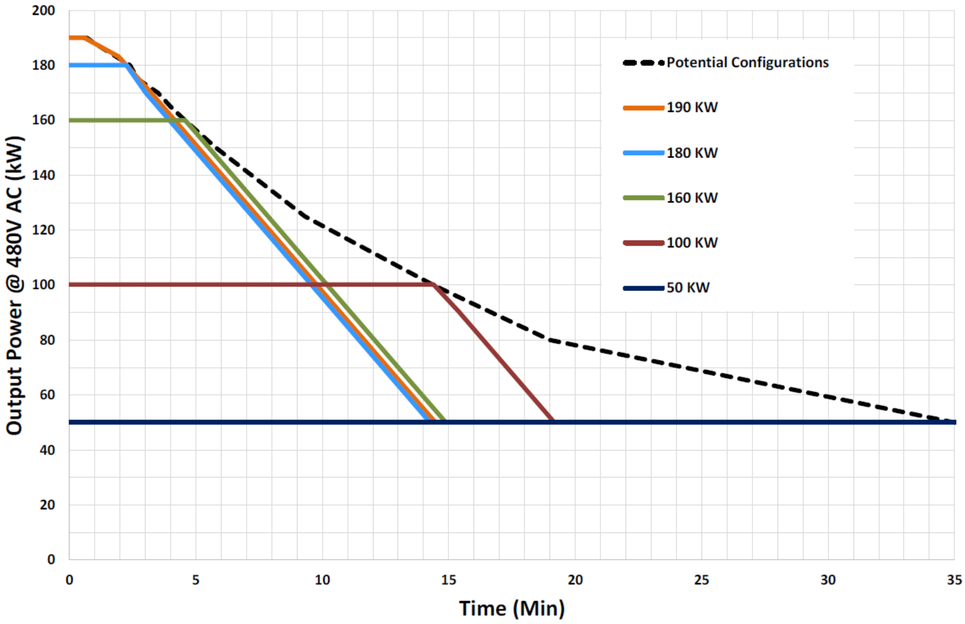

Figure 12 Beacon Power, available operating configurations

3- Railway power system model

In the following sections, the objective of the thesis will be developed in such a way that the reader can recreate the procedure and evaluate the reliability of the project and the results. As commented before, the thesis will study different cases where install a FESS in the power system may be useful:

1- Integrate FESS to current traction station in order to reduce the peak power requested in chapter 4
2- Integrate FESS in order to improve energy transmission by delivering power on time between two traction station, reducing voltage drop and line losses in chapter 4.
3- Integrate FESS to absorb regenerative braking energy and deliver it when a train is moving from a valley to uphill in chapter 6.

The aiming of this subsection is to describe the Swedish railway power system, identify standards and other requirements in order to model it. The reader should be familiar with these concepts to understand the calculations of the following chapters

1- Electrification system
2- Rotary converters
3- Booster Transformer system
4- Trains selected
5- Maximum current limitation
6- Pantograph voltage limitation
7- Line model
8- Type of buses

1- Electrification system

Nowadays, electric mainline railways are fed by three different power systems [23]:

- In the last years, the advance in power electronics for traction motors led to a better speed control of them. Most of the countries with railway electrification done lately use 25 kV Alternating Current (AC) at 50 Hz/60 Hz as a base voltage. This can be seen in the high-speed lines developed in Spain, Turkey, and Italy among others, despite the regional lines work in a different base voltage.
- On the other hand, Direct Current (DC) is used due to the easy speed control of DC motors installed in trains and locomotives, present in those countries where electrification for railway systems was done beforehand the disposal of power electronics and the control of AC motors. Since the national grid has been always an AC system, the convenience of an AC system is desired. Base line voltages in DC power system can be 750, 1500 or 3000 V.
- When commuter motors were used, a AC voltage with reduced frequency was selected in order to control those motors Some counties face the problem of
- Alternating Current (AC) was selected and commuter motors used in other countries. The speed of these types of motors can also be controlled straightforwardly. 15kV, 16.7 Hz is an example found in different places of Europe, for example in Sweden.

A map of Europe showing the three different power systems, in the following figure

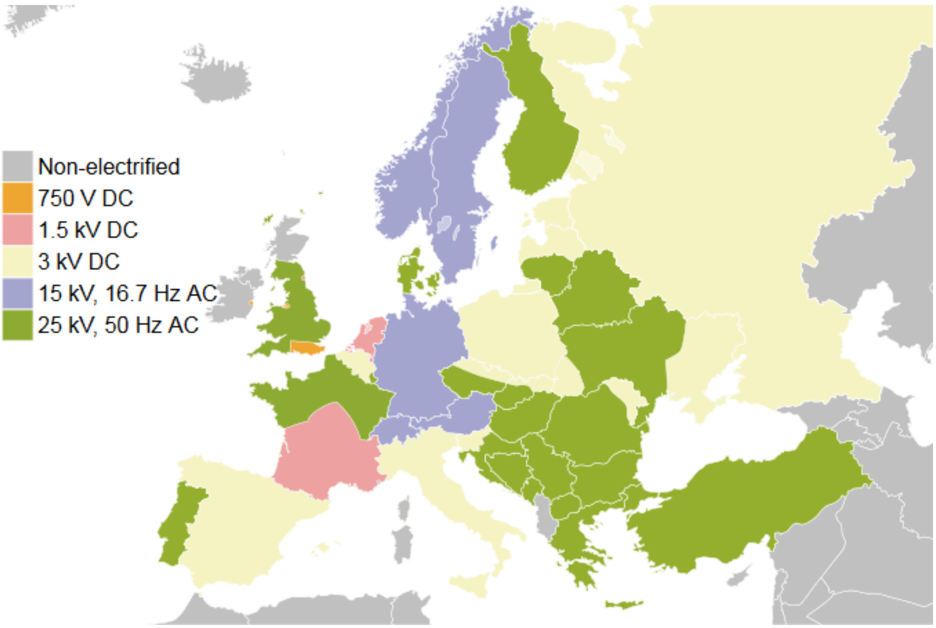

Figure 13 Electrification systems in Europe.

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2- Rotary converters

Access to the current railway power system in Sweden was given from Trafikverket. The overhead line voltage works at 15000V AC, 16.7Hz, synchronized with the public network. Basically, two types of converters can be identified, rotary converters and static converters. Below one example of those converters used in the Swedish network

- Rotary converters (*Roterande omformare* in Swedish), for example: Q38/Q39 *Roterande omformare* from ASEA
- Static converters (Statiska omriktare in Swedish), for example: Megamacs-6 Statiska omriktare from Adtranz or PLUS Statiska omriktare from SIEMENS

In the following figure, an example of a rotary frequency converter and an AC-DC-AC static frequency converter is displayed:

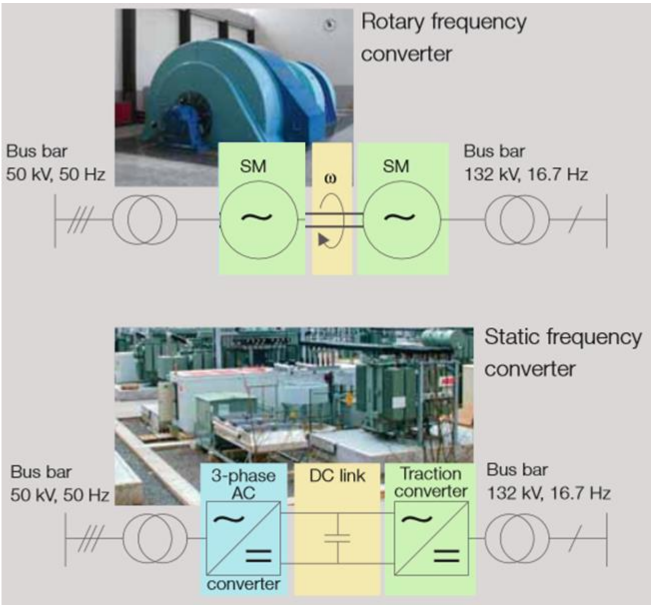

Figure 14 Two types of frequency converters

The rotary frequency converter seen on top of the figure consists of two synchronous machines connected to the same shaft mechanically. The different number of poles in that motors are able to convert the frequency from the national grid to the railway power system, being, also, synchronized. The first one acts as a motor, and the second one as a generator, efficiency is good but the presence of two big motors rotating all time is less desired than a power electronics assembly seen on the bottom of the figure. Countries like Sweden and Norway have been working with rotary frequency converters made of two synchronous machines and nowadays those are being replaced by power electronics converters (not necessarily AC-DC-AC converters). It is not the case of Germany, Austria and Switzerland, where frequency rotary converters were implemented using single-phase machines, operating their transmission system autonomously of the national grid. Frequency was more susceptible to vary since the nets are not synchronized.

Rotary converters are the responsible to feed the overhead line with 16.5kV, 16.7Hz from a 20kV three-phase 50Hz, public network. After some discussions, the Thevenin equivalent of the rotary converters will be modelled as a stiff power supply giving 16500V with the same voltage angle for all rotary converters in the system. No internal resistance is considered.

Figure 15 An example of a rotary converter in Karlstad, Sweden

3- Booster transformer system

Booster transformers are used in electric railway AC catenary feeders to collect the return current from the rails and the earth to the return conductor. In railways, the electric current is taken from the catenary conductor to the locomotive, where the energy is used by electric motors, and fed to the earth connected rails, which are part of the return circuit. From the rails, however, the return current may deviate around to unintended or harmful places like metallic pipe-lines, bridges, communication cables, etc. The stray currents bring about interference in communication systems and other electronic devices due to passing trains. Booster transformers are used to eliminate the stray currents and the disturbances, obliging the return current to flow to the return conductor.

By adding so many converters, one every 5Km approximately, the power lines have a high inductance value.

4- Maximum current limitation

Maximum allowable train current is given in EN 50 388:2005 Table 2. The value for Sweden in Table 2, clause 7, is valid for vehicle drawing current in tractive mode. During regenerative braking the current can exceed this value, due to cos (ϕ)-control (if present) in order to keep the voltage within limits.

Maximum current limitation is 900 A in tractive modes. Higher values in braking mode can be accepted. EN 50388 standards must be followed; figure 15 shows the allowed current levels dependant on the overhead line voltage.

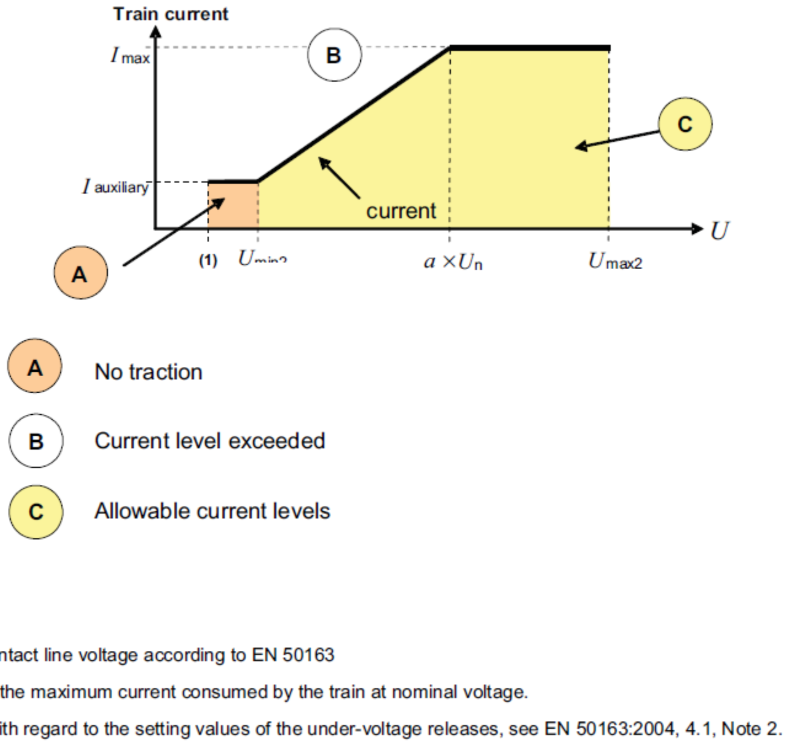

Figure 16 Maximum train current against overhead line voltage

No values of $I_{auxiliary}$ have been found on [24]. Values for *a*, U_{max}, U_n, and U_{min2} are found in [24] EN 50136, EN 50388.

a = 0.95

Umax2= 17,5KV

Un=15 KV

Umin= 12KV

Anyway, when carrying out calculations, current values must not exceed 900A for one train.

5- Pantograph voltage limitation

The minimum values for mean useful voltage at the pantograph under normal operating conditions shall be:

Power supply system	Minimum mean useful voltage $U_{\text{mean useful}}$ at pantograph V	
	Category I, II, III HS TSI lines	Category IV, V, VI, VII CR TSI lines and Classical lines
	Zone and train	Zone and train
a.c. 25 000 V 50 Hz	22 500	22 000
a.c. 15 000 V 16,7 Hz	14 200	13 500
d.c. 3 000 V	2 800	2 700
d.c. 1 500 V	1 300	1 300
d.c. 750 V	N.A.	675
Key N.A.: Not applicable		

Figure 17 Minimum U $_{\text{mean useful}}$ at pantograph

Since Sweden works at 15000V AC 16.7Hz and the line between Duved and Östersund is defined as Category IV, V, VI, VII CR TSI lines and Classical lines, U mean useful = 13500V. During calculations, values lower than 13500 shall not be accepted.

6- Type of train

As a starting point, one typical passenger train and one freight train, figures 17 and 18, which can be found in the Swedish network, are selected in order to have a reference of the maximum power these are able to consume:

Figure 18 185/241/El19/Re Freight train from Bombardier

Figure 19 X52 Passenger train from Bombardier

Specific information of the trains will be given in the following sections. Power for the passenger train is set at 1.59MW and for the freight train 5.6MW, according [3]

7- Transmission line modelling

The appropriate transmission line model (short-, medium, long-line model) in power system steady-state analysis must be used. In [25] the validity for each model is explained. In this case, a power system with a nominal voltage of 15 kV is within the range of short line model. Length of the power line is a parameter to consider when selecting the model, in this study, though, distances from power supply to load will not be longer than 80Km.

Validity of short line Model: Line Length (l) < 80 Km or Nominal Voltage <69kV

Model representation:

$$Z = \left(R_0 + j\omega L_0\right)\cdot l$$
$$= R + jX$$

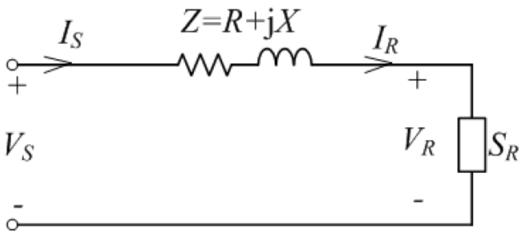

Figure 20 Representation of the short line model

8- Types of buses

In the following sections, current and voltage values will be studied. Power flow at each bus is deified by at least 4 parameters. Generally, there are three types of buses in a system, explained in table 10:

Table 10 Type of buses in power flow calculations

Type of Bus	Voltage Mag. (V)	Voltage Angle (δ)	Active Power Injection	Reactive Power Injection
Slack Bus (Vδ-Bus)	Known	Known	To be solved	To be solved
PV-Bus	Known	To be solved	Known	To be solved
PQ-Bus	To be solved	To be solved	Known	Known

PV-Bus is usually a generator on AVR (Automatic Voltage Regulator) control. PQ-Bus is usually a load or generator without AVR control. In this thesis, trains will be considered as a PQ bus when catenary

[3] http://www.jarnvag.net/

voltage is within limits. When voltage values are below or upper limits, the voltage limit will be fixed and then, trains will be considered as a PV-Bus.

Traction stations, as commented before, will be considered as a Slack Bus with a fixed voltage of 16500V and a 0 degree angle.

A sketch of the line model is displayed below, where it can be seen the presence of booster transformers, the type of bus for each bus and the line impedance.

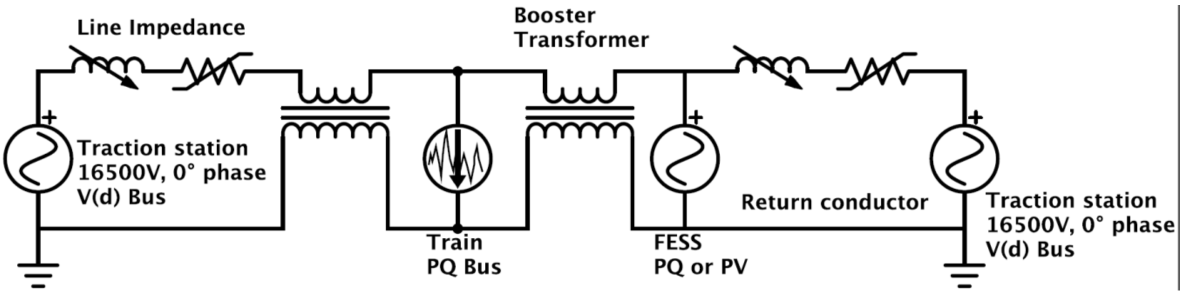

Figure 21 Sketch of the line model

4- FESS to reduce peak power

Description

In the following graph, figure 21, is showed the apparent power load record (minute record) for Duved station in blue. The number of rotating converters (*Antal enheter i drift*) which were in operation is showed with a red line. It is easy to see that one of them is only active few moments a week in order to supply peaks of power that the first converter cannot handle.

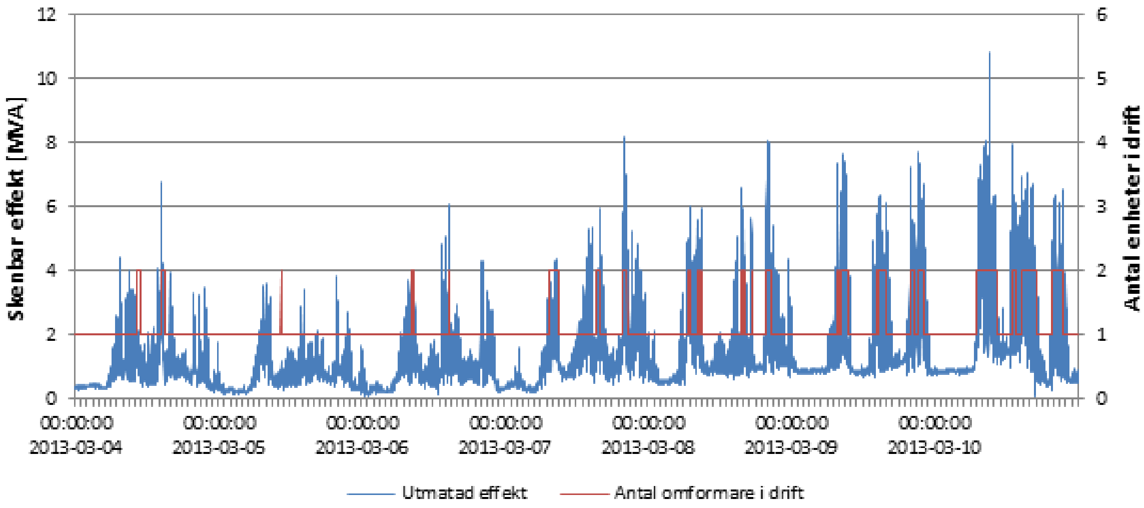

Figure 22 Apparent power load in Duved station and the number of converters working at every minute

Aiming

The intention of this section is to see if it is possible to skip the use of one of the converters by incorporating a FESS, this solution aims to reduce the ratio Peak Power over Average Power. FESS will supply the peak power in order to reduce the load until only one converter is used.

Requirements and assumptions

The only data provided from Trafikverket consists on the power load in Duved; no other stations will be studied. Two rotary converters Q38/Q39 from ASEA are nowadays used in Duved Station; the output power of the converters is displayed in Table 15:

Table 11 Output power for a Q38/Q39 rotary converter

	Output power					
	Continuous		Overload		Maximum	
Q38/Q39	5.8 MVA	350A	8MVA	500A	9MVA	600A

Analysing the previous graph it can be seen that 8MVA is the maximum power requested for most of the days. However the maximum found is 10.8MVA. Knowing that 5.8MVA is the continuous power that a converter can supply (it is not recommended to overpass that value), the power decided for the FESS has to be at least 8-5.8=2.2MVA in order to supply the maximum peaks. Since not too much data is available a safety factor to over dimension the FESS is chosen. The first calculation will consider a 3MW FESS.

As seen before, the cost of the installation is highly dependent on the MW installed, so, fewer MW cheaper the installation will be. It is pointless dimension the FESS to handle the peaks of 10.8MVA that occurs once a week, that it is the reason why 3MW is considered enough.

Since the intention of this chapter is to reduce the peak power tariff to the half (only one converter in use), the maximum continuous power supplied will be 5.8+3=8.8MVA. Power above this number will entail an undesired overload of the converter.

As a starting point a 10 minutes discharge FESS is the decision. Then, the characteristics of the FESS are:

- Power: 3MW

- Energy stored: 500KWh

Development and strategy:

An average of the power delivered from the station has been calculated for every 15 minutes, these values have been set as a target for the power delivered from the converter, in this way the converter is delivering the same power during 15 minutes and the flywheel is storing or delivering energy depending if the current load of the train is higher or lower than the average for these 15 minutes. However, some restrictions have to be fulfilled, the flywheel must have enough energy to deliver the power requested and at the same time, the maximum power given has to be equal or less than 3MW.

4.1 Iterative calculations

In figure 22, the result of the power distribution according the strategy chosen for one day is:

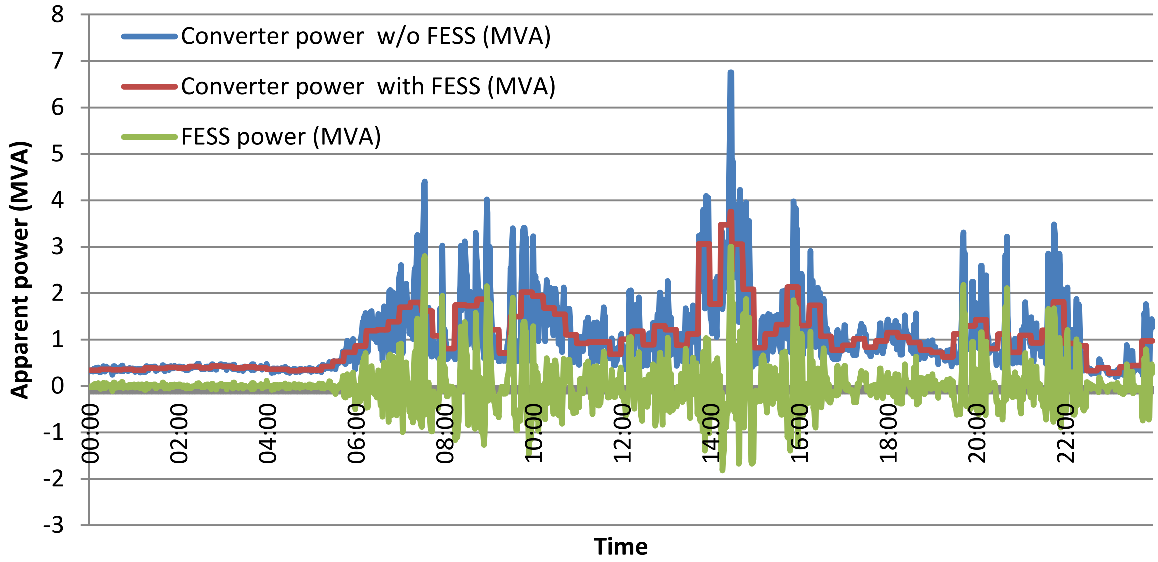

Figure 23 Apparent power distribution

The red line is then the average power every 15 minutes, the apparent power the converter is delivering along the day. The green line represents the power delivered from the flywheel and the blue line is the raw data from the converter without flywheel.

In order to see how is the state of charge/discharge for the flywheel, the worst case scenario is chosen, and when the peak loads and energy requested are bigger.

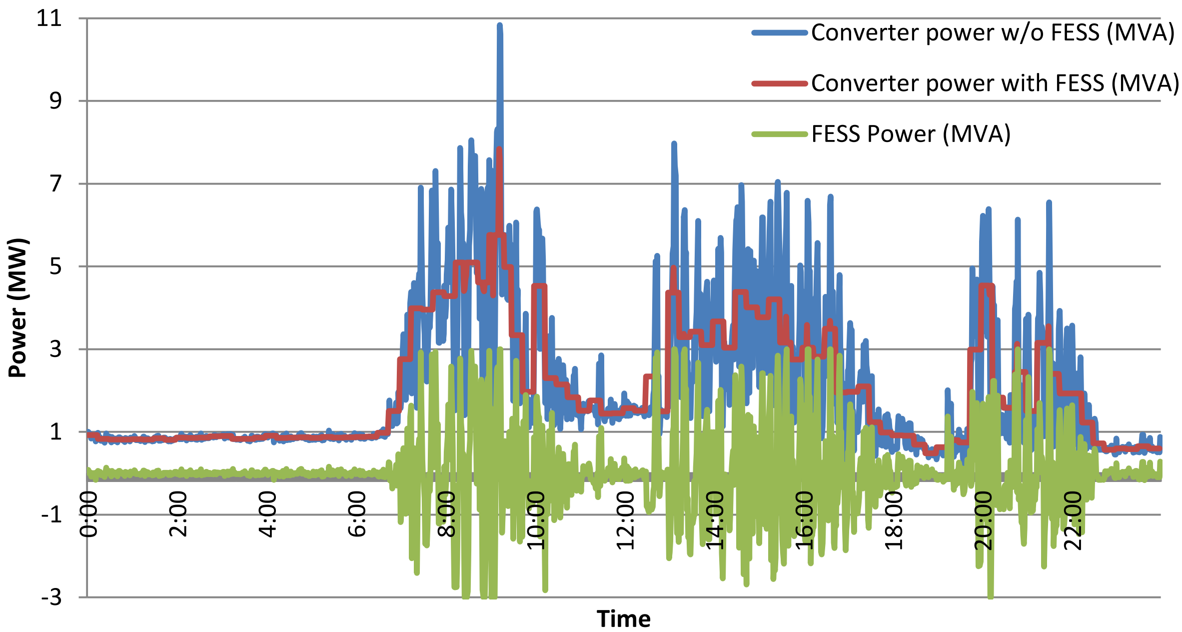

Figure 24 Apparent power distribution

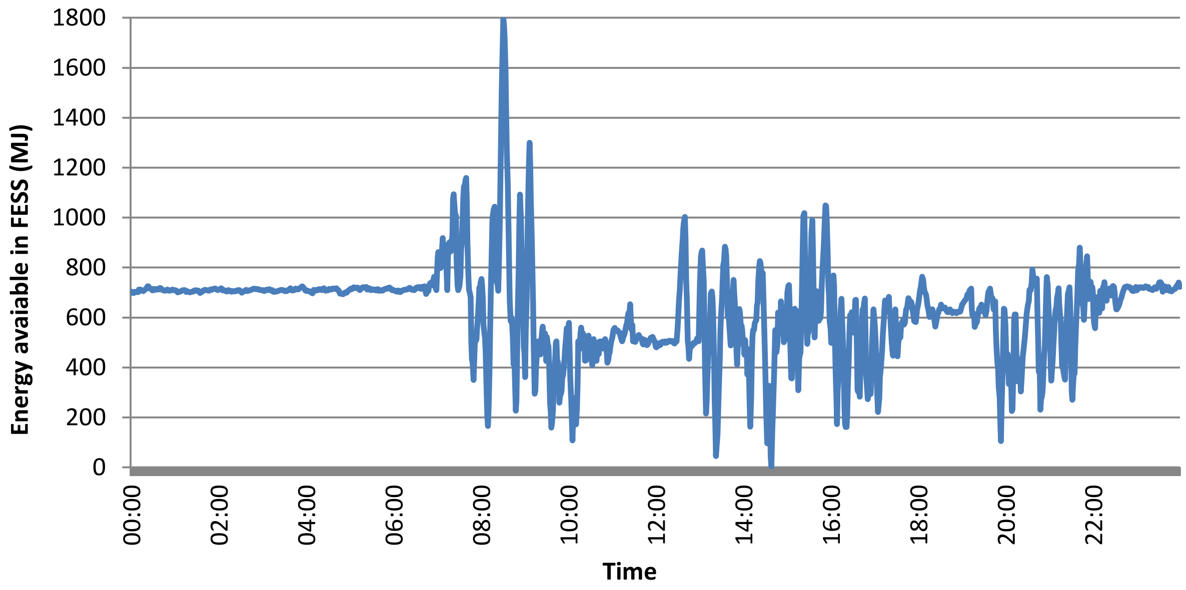

Figure 25 State of charge/discharge for the FESS

The use of the FESS is maximized, for the worst case scenario and for the current strategy, the flywheel reaches the maximum and the minimum energy stored.

Now it is time to see how the incorporation of a FESS affects the peak load reduction for an entire week. The first graph shows the original power distribution in a blue line and the power available from the converters in red. One converter is capable of giving 5.8MVA, and two, 11.6MVA.

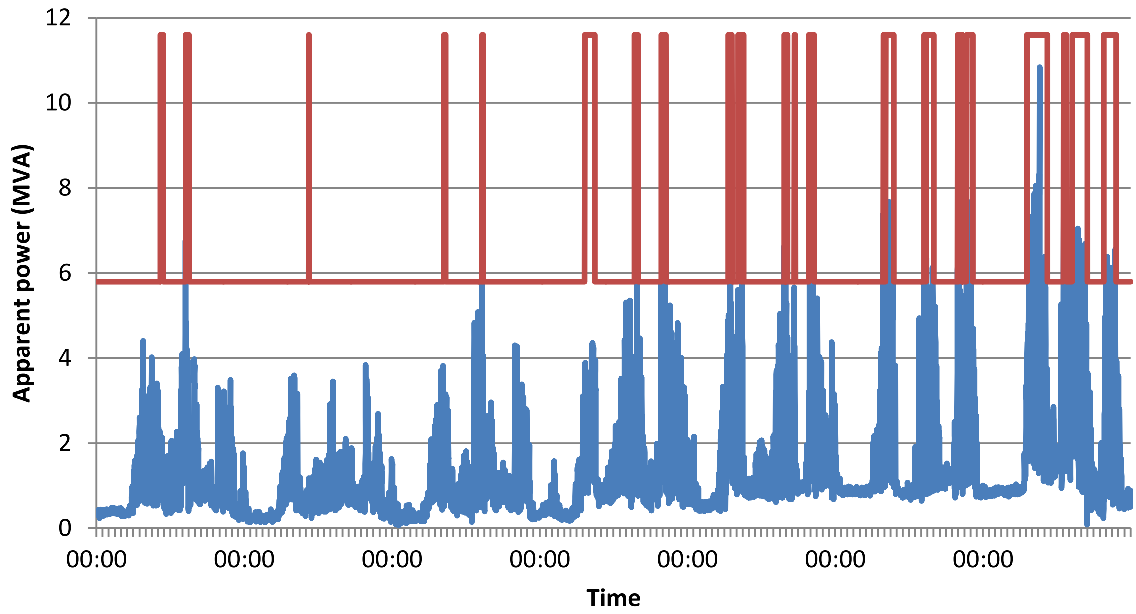

Figure 26 Apparent power load in Duved station and maximum power available

In the following figure, the power load of the flywheel in purple, the power load of the converters in green. Anytime that the green line is under the red one the power can be given for only one converter.

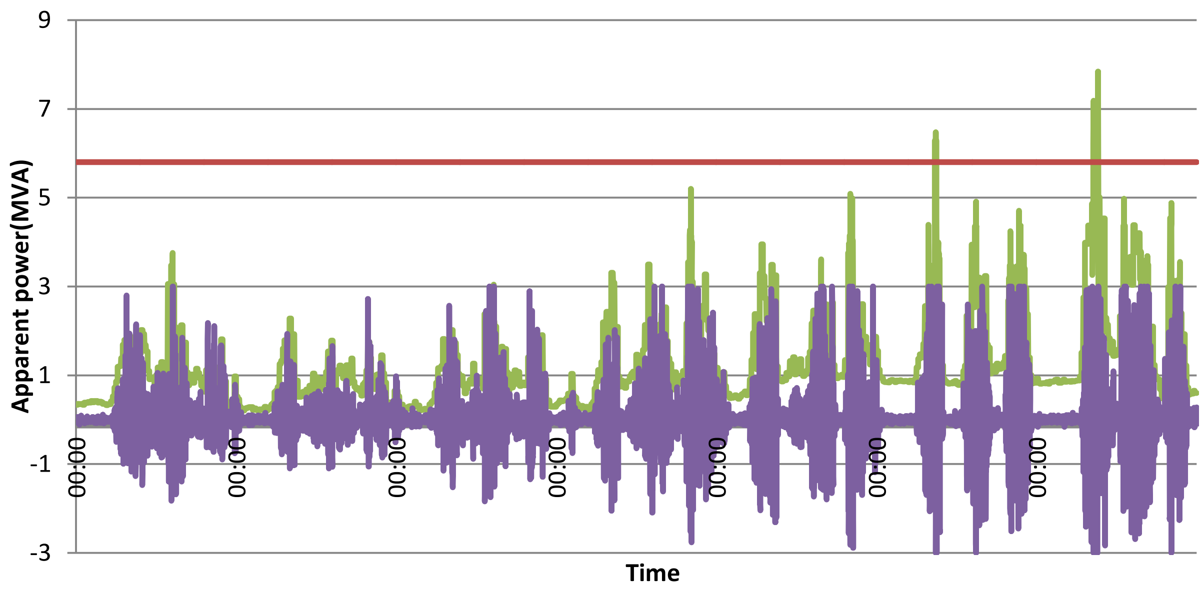

Figure 27 Apparent power distribution

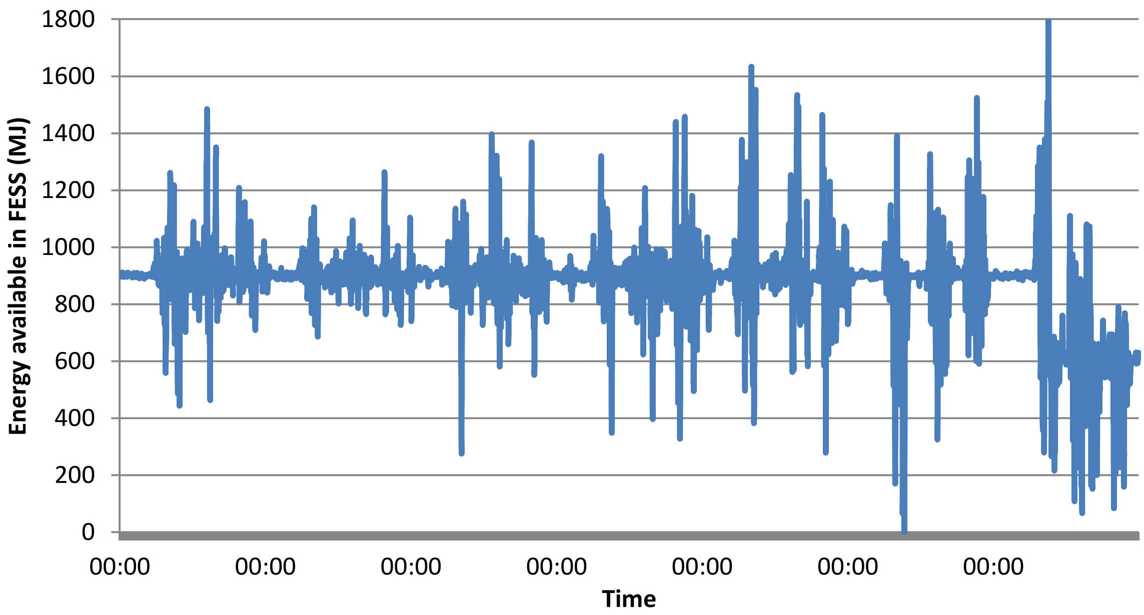

Figure 28 State of charge/discharge for the FESS

FESS installed in a traction station reduces the power requested for the grid by storing or delivering the energy when it is needed. It can be a solution when more power is requested for a traction station and cannot be given from the national grid because difficulties on access or power plants are far away. This solution supports the current station giving more flexibility and independence. This case can be an alternative to changing/upgrading one converter in traction station for one bigger and instead, incorporate a FESS.

4.2 Economic evaluation

The peak power reduction will be 5.8MVA, since the aiming is to not use one of the converters (that can work as a back-up in case of failure of the other one). Trafikverket provided the power tariff, which is 329 kr/KW (36,19US$/KW) yearly.

Considering a 5800KW load reduction, this is:

$$Annual\ cost\ reduction = 5800\ KW \cdot 36{,}19\frac{\text{US\$}}{\text{KW}} = 209902\ US\$\ per\ year$$

However, each energy supplier has a deal with every company even different depending on the place where the deal is taken. Experts from Trafikverket explained that the deal with the energy supplier Vatenfall is that the power capacity tariff is not set by the maximum power requested to the company (as usually is) but with an average of it. They use the unit MWh/h, to see the energy used in one hour, which finally is a measure of the average power consumed in one hour. With this kind of deal, no advantages are present when incorporating a FESS in terms of power tariff reduction since the FESS is just levelling the power requested for the converters, being the average power consumption the same, but with less power peaks. However any energy supplier will be satisfied if for the same energy consumed the power requested is the half, so, a new deal can be trade and some savings in the power tariff achieved.

From the previous graphs, it can be seen that an 1800MJ (500kWh) FESS is slightly bigger than what it is actually needed. Since the trains are moving in a closed network it is easy to identify the position of them, and as a consequence the load they need. Then, the flywheel can be charged or discharged to be prepared to supply or to store energy respectively. Looking the SOC of the FESS, 1800MJ can be reduced to 1500MJ in the best cases, the result, a cheaper FESS. However, this decision is tough to decide since not too much data is available. Both cases are evaluated:

Now, the cost per kW for a 1500MJ (416.67 kWh by 0.139h discharge) is:

$$Corrected\ cost\ \frac{US\$}{KW} = Energy\ \left(\frac{US\$}{KWh}\right) \cdot 0.139\left(\frac{KWh}{KW}\right) + \text{Power}\left(\frac{US\$}{KW}\right) + Installation(\frac{US\$}{KW})$$

Corrected cost is 1000US$/KW, considering 150US$/KW for installation.

The corrected cost for a 10 minutes discharge FESS, was calculated previously, 1100US$

An installation of 3MW, 1500MJ will cost 3M US$.

An installation of 3MW, 1800MJ will cost 3.3M US$.

Interest rate is fixed to 0.75% according actual regulations

Energy tariff is fixed to 75öre/kWh (0.11 US $/kWh), according Trafikverket.

The payback is:

Table 12 Payback time, case 1

	FESS Power	
	3MW, 1500MJ	**3MW, 1800MJ**
Payback time [years]	14	15

5- FESS to be charged with regenerative braking

Description

All modern locomotives incorporate regenerative braking; the power is fed back to the overhead line to be used by other trains or fed back to the public network when the train it is braking. Throughout a travel, a modern train is requesting power when it needs to accelerate and giving power back when it needs to decelerate; it is in that point where it comes the importance of energy storage: instead of supplying power to the train from remote stations, a FEES can absorb energy from regenerative braking to be charged and supply it to the train when it is requesting power. For abrupt and sudden changes in the slope (e.g. in between a big down slope and a big ascent slope), a FESS that can manage the flow of power from closer distance than a traction station will entail to an increase of performance and energy savings.

Aiming

The aiming of this section is:

- To compare the performance of the power system when incorporating a FESS by displaying overhead line voltage and power limitation.
- To quantify energy savings when integrating a FESS in the power system and the payback time of the installation needed.

Requirements and assumptions

1- Topography

As bigger is the slope when the locomotive is moving downhill more energy will be regenerated by the train and as a consequence more energy will be available on the flywheel to boost the train when is moving uphill. In this section it has been considered that:

- A 185/241/El19/Re from Bombardier is descending 100m in 5km; this is a slope of 2%, equivalent to 1.14 degrees. The slope is considered constant along the way.
- In the lowest point, a FESS is installed.
- Train is ascending 100m in 5km again, with the slope constant all the way.

- The lowest point will be placed at Mattmar station (seen in the previous chapter) in order to keep the same line values as the previous section.

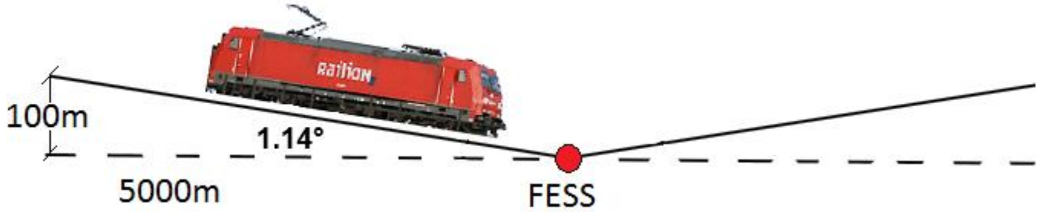

Figure 29 Sketch of the gradient

These numbers are not common on the south Swedish railway network but it is an example of the topography in hilly places, especially in the north-west of Sweden [26]. This “extreme” situation will be useful in order to compare the increase on performance and energy savings for a FESS.

2- *Maximum energy recovered when braking*

According train parameters, Appendix A, train dynamic mass is 1054.2t. Considering that the train maintains the same speed (90km/h) the energy that the train must dissipate all the way down is equivalent to the potential energy:

$$E\ [MJ] = \frac{m[kg] \cdot \mathrm{g}\left[\frac{\mathrm{m}}{\mathrm{s}^2}\right] \cdot \mathrm{h[m]}}{10^6} = \frac{1054200 \cdot 9.81 \cdot 100}{10^6} = 1034.17\ \mathrm{MJ}$$

The friction forces depend strongly on the speed:

$$F_N\ [kN] = 12.07 + 0.07722 \cdot \mathrm{v}\left[\frac{\mathrm{km}}{\mathrm{h}}\right] + 0.003735 \cdot \mathrm{v}\left[\frac{\mathrm{km}}{\mathrm{h}}\right]^2 = 49.27kN$$

Once the friction forces are calculated the energy loses are obtained by multiplying the forces by the length of the slope (approximately 5000m).

$$E_{losses}[MJ] = \frac{F_N[\mathrm{kN}] \cdot d[m]}{10^3} = \frac{49.27 \cdot 5000}{10^3} = 246.35\ \mathrm{MJ}$$

Then, the energy that the train is able to recover when braking will be the energy that the train must dissipate, subtracting the energy loses and multiplying by the efficiency of the motor and power electronics to convert the mechanical energy into electrical.

$$E_{braking}[MJ] = (E[MJ] - Elosses[MJ]) \cdot \eta = (1034.17 - 246.35) \cdot 0.88 = 693.28\ \mathrm{MJ}$$

The maximum energy that the train is able to return to the power system is **693.28MJ**

According specifications there is a limitation of 240kN as a maximum electric braking effort. If the train request more effort than this value, other methods of dissipate energy are used.

In order to check if all the energy that must be dissipated is regenerated, the braking effort should be lower than 240 kN. The braking effort is calculated by dividing the maximum energy that needs to be dissipated by the distance that the train is braking.

$$F_{braking\ effort}[kN] = \frac{Energy\ [MJ]}{d\ [m]} \cdot 10^3 = \frac{693.28MJ}{5000m} \cdot 1000 = 138.66KN$$

Indeed, 240<138.66, so all the energy can be returned to the overhead line as regenerative energy.

3- *Active and reactive power for regenerative braking.*

The power that the train is giving back to the overhead line is obtained by measuring the time that the train is braking,

$$t\ [s] = \frac{d[m]}{v\ [\frac{m}{s}]} = \frac{5000}{25} = 200\ s$$

Along these 200s the regenerated power is:

$$P\ [MW] = \frac{E[MJ]}{t\ [s]} = \frac{693.28MJ}{200s} = 3.46\ MW$$

The train is providing 3.46MW to the overhead line, the voltage on that point, thus, will increase. According [24] and [EN 50388] the maximum overhead line voltage and other requirements must be fulfilled:

> *"The vehicle must not cause the line voltage to increase above 17.5 kV in regenerative braking".*

There are several possible technical solutions in order to meet this requirement. One possible solution is to limit the line voltage at the new rolling stock to 17.5 kV. Another solution is a control of cos (φ) during, as suggested by the figures 32 and 33 below.

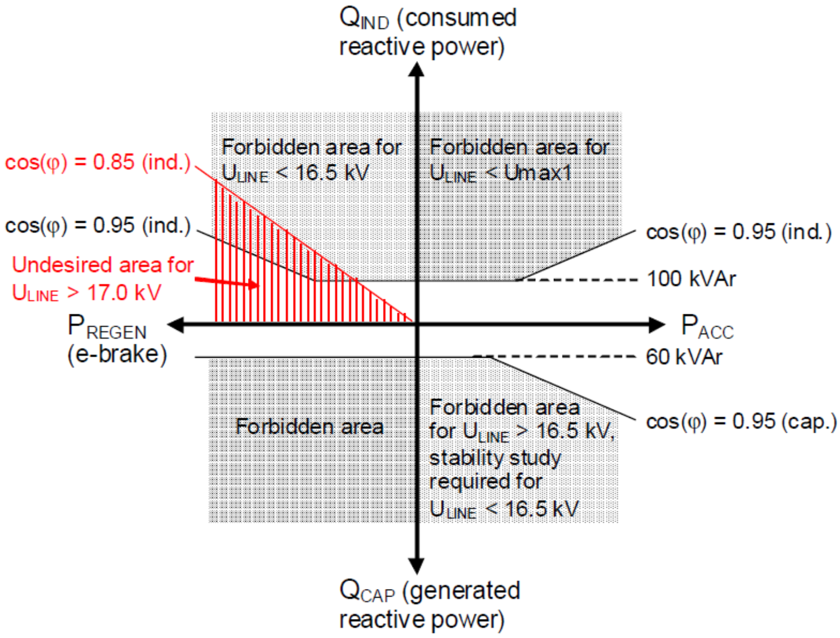

Figure 30 Suggested cos (φ)-control in regenerative braking.

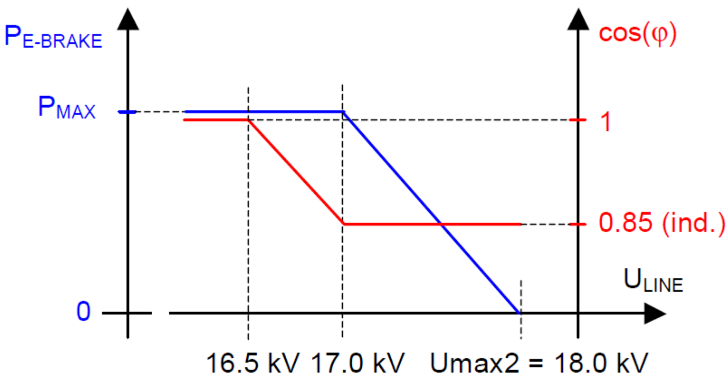

Figure 31 Suggested power limitation and cos (φ)-control in regenerative braking.

From the previous figures it can be seen that the regenerated reactive power is limited to a small range of values, limiting the option to control cos (φ). In regeneration mode (electrical braking) the train shall not behave like a capacitor greater than 60 kVAr at any regenerative power, i.e. capacitive power factor is prohibited during regeneration. The exception of 60 kVAr capacitive reactive power is to allow the possibility to have filters on the high voltage side of the train/traction unit. These filters shall not exceed 60 kVAr capacitive. For other reasons an inductive reactive power is undesired. Thus, in the following calculations regenerated reactive power will be set to 0MVAr, being the regenerated active power 3.46MW as calculated in the previous page.

4- Active and reactive power for traction mode

With the assumption that the train will keep the same speed all the way up at 90km/h, the energy that the train may require is the sum of the potential energy and the energy losses (calculated in the previous page) divided by the efficiency to convert electrical to mechanical energy.

$$E_{uphill} = \frac{E[MJ] + Elosses[MJ]}{\eta} = \frac{1034.17 + 246.35}{0.88} = 1455.1 \text{ MJ}$$

The power requested will be the energy divided by the time:

$$P = \frac{E_{uphill}[MJ]}{t[s]} = \frac{1455.14}{200} = 7.27MW$$

The rated electric power of the train is 6.364MW at a rated voltage of 15KV. When the power supply is far from the load, overhead line voltage might be lower than 15kV and the power received to the train as a consequence will be lower than these 6.364MW: It means that the train will not receive all the power it needs to maintain constant speed. On the following calculations will be considered that:

- No reactive power will be requested from the train.
- The "equivalent resistance" of the train will be the parameter to fix the power requested.

$$P[W] = \frac{|\underline{U}|^2[V]}{r\,[\Omega]}$$

Where *P* is the rated Power and $\underline{U}$ the magnitude of the voltage. The "equivalent resistance", *r*, at the rated power and voltage is

$$r = \frac{15000^2}{6.364 \cdot 10^6} = 35.36\Omega$$

In any case the equivalent resistance can be lower than this value, since a smaller resistance will induce a bigger current than can damage the converters of the locomotive. This 35.36Ω is set to force the train to consume the maximum power when is driving uphill.

5- Active and reactive power for FESS

The energy system will absorb 3MW when the train is braking and will deliver 3MW when the train is requesting power. Since the train has been set to not consume reactive power the FESS will be set to deliver and to absorb 0kVar. The capacity for the FESS will be studied on the following pages.

5.1 Iterative calculations

The calculations are done is a discrete way; the train is moving 0.5 km forward until the next state of the power system is calculated, this is 20 points for a 10km travel. Moreover all the points are calculated as a steady-state, i.e. no transient behaviour is included in the calculations.

1st iteration

In the first iteration, the power system will be represented by two power supplies and one train moving from 53.5 to 63.5 km (Duved as a reference). The unknown variable *x* represents the distance in Km from Duved Station. Figure 29 shows the system without FESS and Figure 30 includes a FESS placed at 58.5km before the train reaches that point.

Model

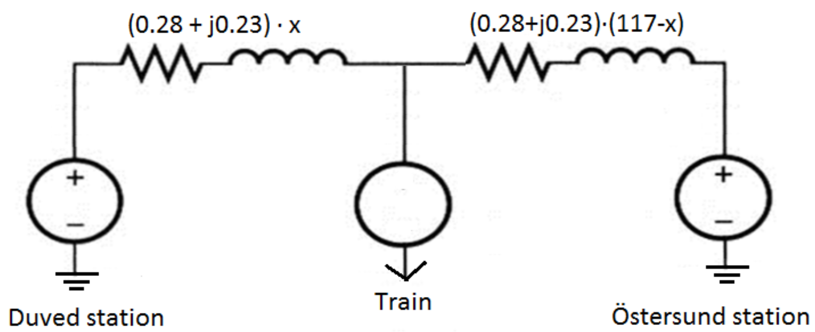

Figure 32 Model without FESS

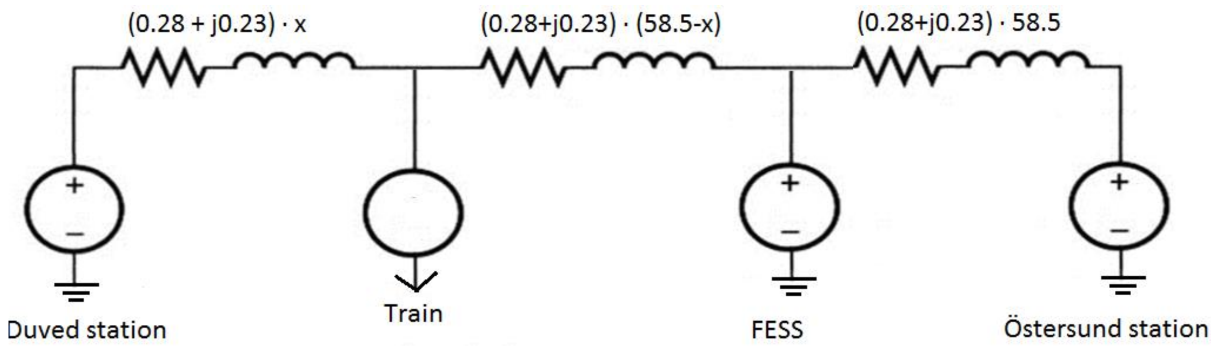

Figure 33 Model without FESS

Note: The equations that define the system are displayed on the Appendix B

Results

The first result displayed is the comparison of the overhead line voltage along the downhill (53.5 to 58.5 km) and uphill (58.5 to 63.5 km).

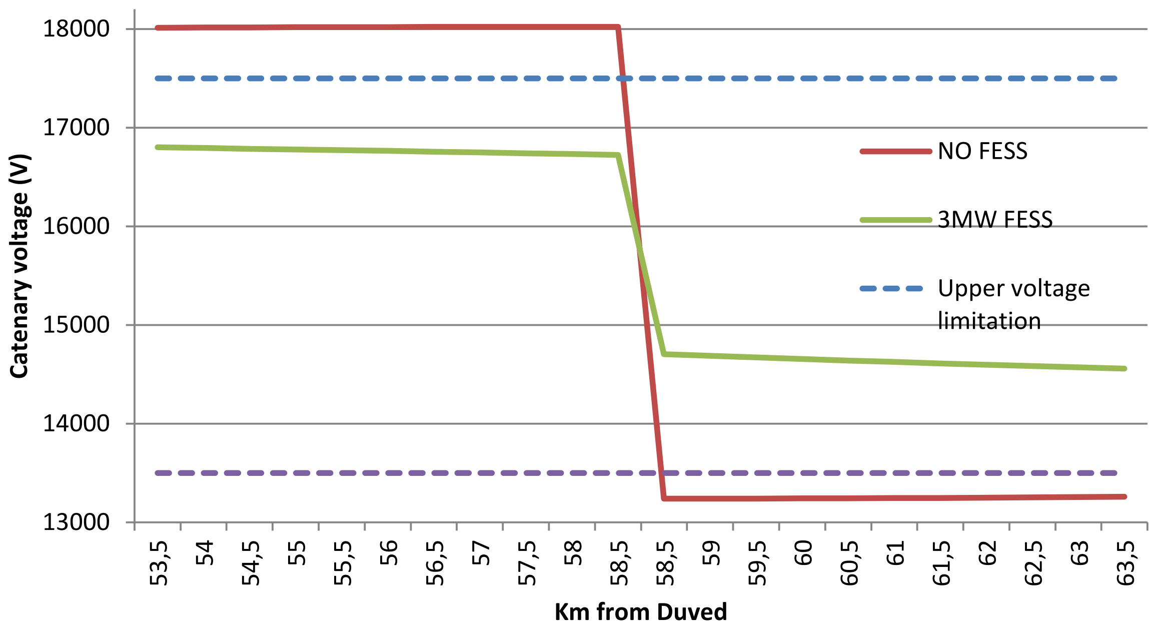

Figure 34 Overhead line voltage at different points from Duved

Where the red line is the overhead line voltage for a system without energy storage, the green one represents the overhead line voltage for a system that incorporates a 3MW flywheel. The blue and purple lines are the voltages for the overhead line to meet the requirements (17500V and 13500V respectively).

The analysis that can be done is the following:

NO FESS:

During downhill, the voltage at the train rises more than 17500V, so the train has to reduce the amount of energy that is giving back to the overhead line in order to accomplish the regulations. Similarly, the overhead line voltage decreases more than 13500V during uphill, what it means that the train has to request even less power, this is that the “equivalent resistance” must be bigger or which is the same, the driver cannot request full power for the train.

Due to overhead line voltage is less that the rated voltage when train driving uphill, power received to the train will be less than 6.364MW. In the following figure the power flow on the train for each point of the line.

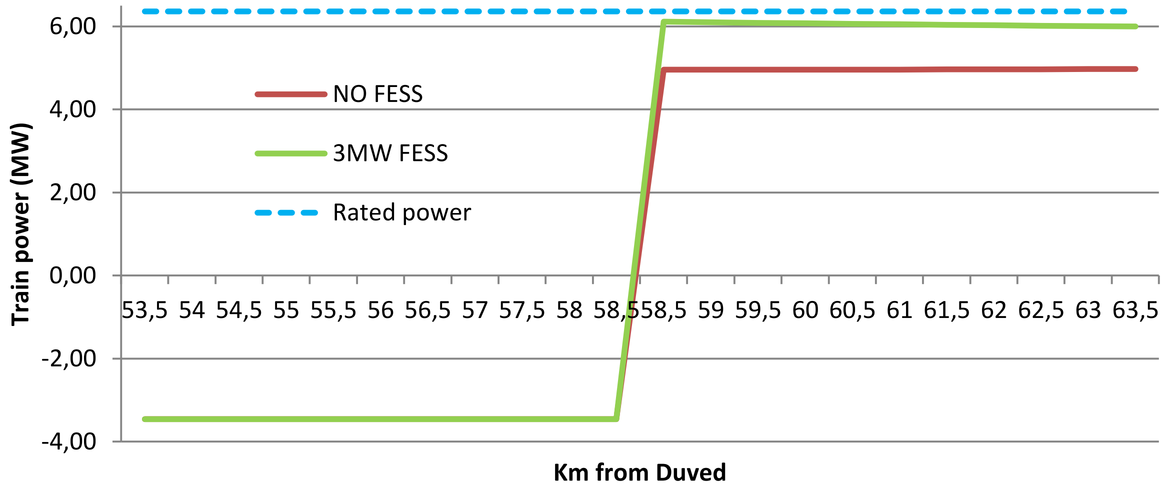

Figure 35 Overhead line voltage at different points from Duved

The graph shows that without FESS (red line) the power is limited to:

$$\text{Power limitation} = \frac{4.96\ \text{MW}}{6.634\ \text{MW}} \cdot 100(\%) = 74.39\%$$

The power limitation implies a reduction of the speed of the train, reducing the time to drive uphill.

3MW FESS:

The previous graphs are displaying voltages within regulations. However, there is some power limitation that is quantified here:

$$\text{Power limitation} = \frac{5.99\ \text{MW}}{6.634\ \text{MW}} \cdot 100(\%) = 90.29\%$$

The energy storage requested for the FESS will be the power delivered and absorbed multiplied by the time is working, this is:

$$\text{Energy storage } = 3\text{MW} \cdot 200\ \text{s } = 600\text{MJ} = 166.67\ \text{kWh}$$

Further Calculations:

The next iterations of calculations will consider:

- Voltage values must be within regulations for the case without FESS.
- Different values of power given by the FESS will be studied.

2n iteration:

Only changes in the model without FESS:

- Voltage at the overhead line will be forced to be 17500V all the way down. Forcing that voltage, the maximum power the train can supply will be found (This value must be smaller than the one set in the previous section, this is lower than 3.36MW). The value found is the maximum power that can be recovered within regulations. When driving uphill the voltage will be forced to be 13500V, it means that the power requested for the train will be less than the maximum (it means that the "equivalent resistance must be bigger than 35.36Ω as explained before).

Model

Note: The equations that define the system are displayed on the Appendix A

Results

Overhead line voltage and power flow is displayed in comparison to the first iteration.

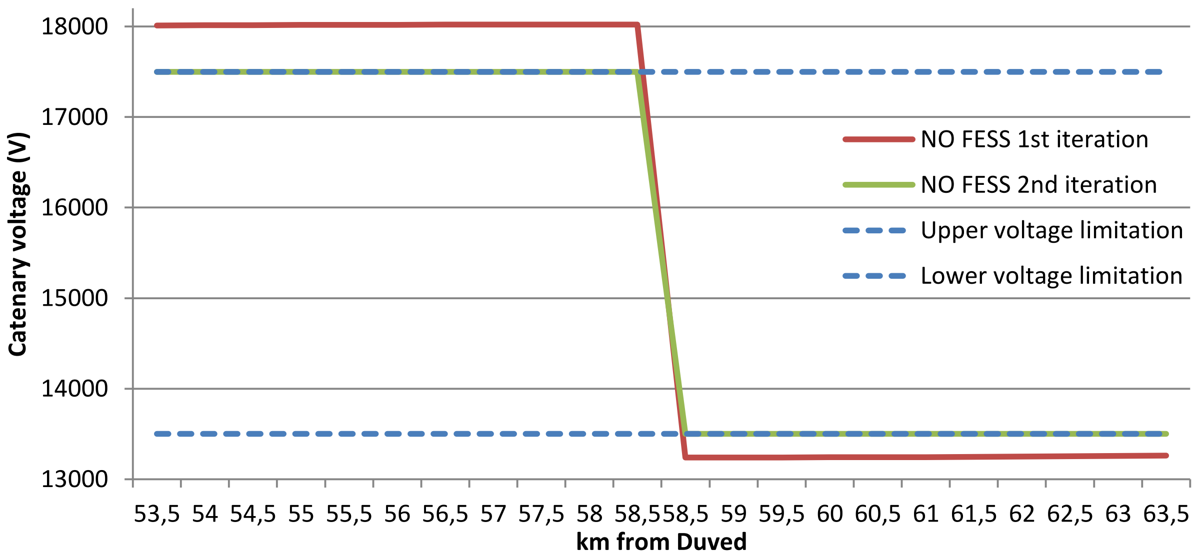

Figure 36 Overhead line voltage at different points from Duved

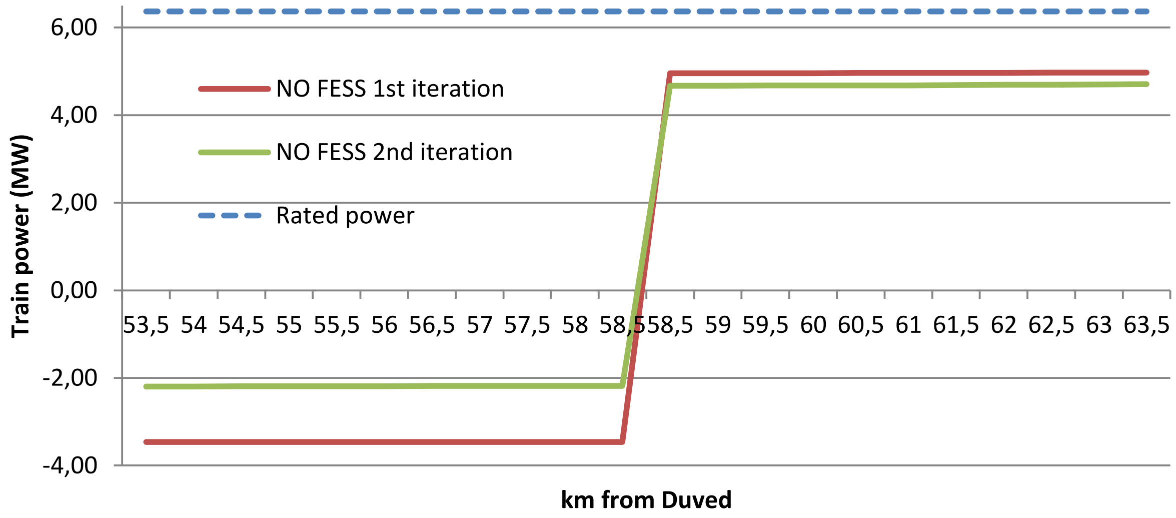

Figure 37 Overhead line voltage at different points from Duved

Analysis:

The voltages are within limitations but at the same time less power is regenerated, so less efficient is the system. This also means that the limitation of power received by the train is even worst:

$$\text{Power limitation} = \frac{4.67\ \text{MW}}{6.364\ \text{MW}} \cdot 100(\%) = 70.39\%$$

Difference of power regeneration is:

$$Power\ regeneration\ difference\ (\%) = \frac{2.20}{3.34} = 65.86\%$$

In other words, the “wasted”energy due to fulfil regulations is:

$$Wasted\ energy = (3.34MW - 2.20MW) * 200s = 228MJ = 63.33\ kWh$$

The values for a power system without FESS are the ones obtained in this iteration.

3rd iteration

Only changes in the model with FESS:

- As higher is the value of the power that the Flywheel is able to deliver and absorb, less power limitation will be seen in the train, but the system itself will be more expensive. On the other hand, as lower is the value of that power, more power limitation will show up. In this section it will be found those values of power that:
    - ¤ As low as possible that maintains the system within regulations
    - ¤ As high as possible that achieves no limitation on power for the train.

For the first point it will be set that the power delivered is the one that makes the overhead line voltage at 17500V when downhill and check if the overhead line is more than 13500V when uphill. The reason for this calculation is that, since the values of the slope are high, finding out the minimum dimension of a FESS that satisfy requirements will mean that it is known the dimension of a FESS in order to provide a better performance and energy savings to any systems with tracks up to 2% of slope.

For the second point it will be set that the rated power of the train is 6.634MW when driving uphill, with a fixed resistance of 35.36Ω, this is a catenary voltage of 15000V. The power of the FESS will be obtained.

Model

Note: The equations that define the system are displayed on the Appendix B

Results

Overhead line voltage and power flow is displayed in comparison of the first iteration (3MW FESS)

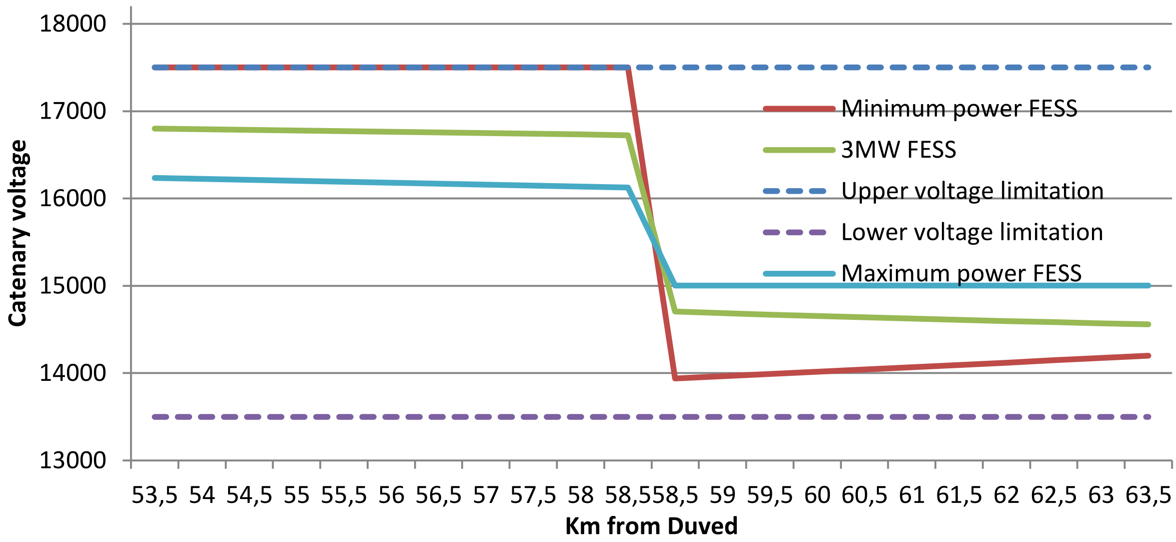

Figure 38 Overhead line voltage at different points from Duved

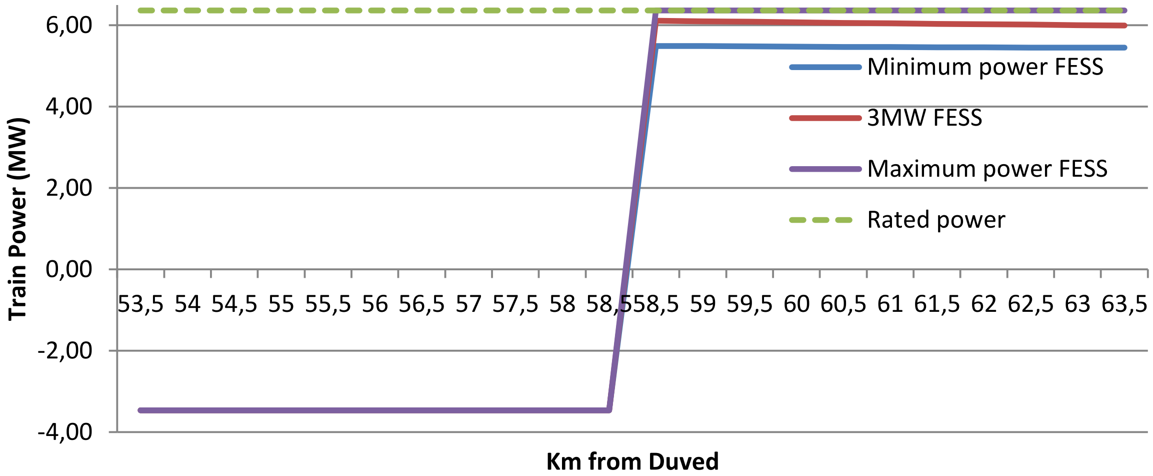

Figure 39 Train power at different points from Duved

Minimum power FESS

The minimum power for a FESS that satisfies requirements is **1.34MW**. This ensures to recover all the regenerative braking without overpassing 17500V. However, there is some power limitation that is quantified here:

$$\text{Power limitation} = \frac{5.45\ \text{MW}}{6.364\ \text{MW}} \cdot 100(\%) = 85.63\%$$

The energy storage requested for the FESS will be the power capacity multiplied by the time it is working, this is:

$$\text{Energy storage } = 1.34\text{MW} \cdot 200\ \text{s } = 268\text{MJ} = 74.44\ \text{kWh}$$

Maximum power FESS

A capacity of **4.19 MW** ensures no power limitation. The energy storage requested for the FESS will be the power capacity multiplied by the time it is working, this is

$$\text{Energy storage } = 4.19\text{MW} \cdot 200 \text{ s } = 838\text{MJ} = 232.78 \text{ kWh}$$

Cost investments for each flywheel capacity will help to quantify which one is better cost-performance option

5.2 Economic evaluation

When evaluating the results it has been considered the difference between the initial power system without FESS, set as a reference, and the system that integrates the FESS. The total amount of energy savings is quantified in a list of 5 points:

1- Energy savings from Duved due to less line losses: Current values are low with FESS.
2- Energy savings from Östersund due to less line losses: Current values are low with FESS
3- Energy losses from FESS to the train due to line losses: Current values appear only in a system with FESS
4- Energy savings from Duved in less Energy delivered during the discharge of the FESS
5- Energy savings from Östersund in less Energy delivered during the discharge of the FESS

In the following lines will be presented how these numbers have been obtained when comparing a system with 3MW FESS and the initial system. The comparisons for different values of the capacity of the FESS are showed with less detail.

3MW FESS compared to NO FESS

1- Energy savings from Duved due to less line losses

The energy savings are calculated as a summation of the difference of the square of currents with and without FESS, multiplied by the resistance of the line and time between every consecutive measurement.

$$Energy\ savings = \sum_{i=53,5}^{63,5} r \cdot \mathrm{i} \cdot (Id_i^2 - Idf_i^{\,2}) \cdot \mathrm{t_i}$$

r is the resistance of the line per km r=0.28Ω/km.

i is the Km from Duved Station.

Id_i is the current from Duved in a power system without FESS at the measurement *i.*

Idf_i is the current from Duved in a power system with FESS at the measurement *i.*

The number of elements in the summation is 20, the values of *Idi* and Idf_i are calculated every 0.5Km as explained before.

t_i will be the time difference between two concurrent measurements, for downhill is:

$$t_i\ [s] = \frac{d[m]}{v\ [\frac{m}{s}]} = \frac{500}{25} = 20\ s$$

Since the speed is constant (90km/h=25m/s) all the way down.

The speed all the way up is decreasing since the train cannot be provided with the energy it requires to keep it at 90km/h. The time for each iteration will be obtained by the assumption than the train keeps the same speed along every measurement. The following formula is used to obtain the time:

$$E_p + E_{losses}(t_i) + Ec = \frac{P_{train}}{t_i}$$

E_p will be the potential energy needed for the train while driving uphill, for every 500m.

$$E_p\ [MJ] = \frac{m[kg] \cdot \mathrm{g}\left[\frac{\mathrm{m}}{\mathrm{s}^2}\right] \cdot \mathrm{h[m]}}{10^6} = \frac{1054200 \cdot 9.81 \cdot 10}{10^6} = 103.417\ \mathrm{MJ}$$

E_{losses} will be the energy losses due to friction with the air:

$$F_N\ [kN] = 12.07 + 0.07722 \cdot \mathrm{v}\left[\frac{\mathrm{km}}{\mathrm{h}}\right] + 0.003735 \cdot \mathrm{v}\left[\frac{\mathrm{km}}{\mathrm{h}}\right]^2$$

$$E_{losses}[MJ] = \frac{F_N[\mathrm{kN}] \cdot d[m]}{10^3} = \frac{(12.07 + 0.07722 \cdot \frac{0.5}{\mathrm{t_i}/3600} + 0.003735 \cdot (\frac{0.5}{\mathrm{t_i}/3600})^2) \cdot 500}{10^3}$$

E_c will be the kinetic energy available due to the decrease of speed:

$$E_c[MJ] = \frac{\frac{1}{2} \cdot \mathrm{m[kg\,]} \cdot (v_{i-1}{}^2 - v_i{}^2)\left[\frac{m}{s}\right]^2}{10^6} = \frac{1}{2} \cdot 1054200 \cdot (\mathrm{v_{i-1}}{}^2 - v_i{}^2)$$

From those numbers the time for each iteration can be found. The detailed information can be found on the Appendix A.

The data of the current flowing from Duved is displayed on the following figure:

Note: Negative current means that the current is given back to the traction station.

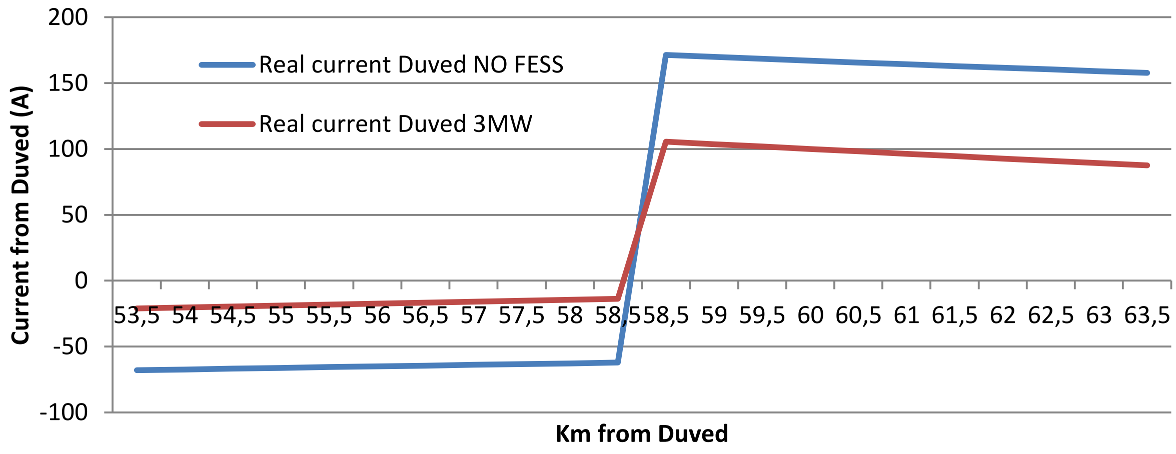

Figure 40 Current from Duved when the train is moving

Total energy savings:

Energy savings= $7.20\cdot10^7$ J = 19.99KWh.

2- Energy savings from Östersund due to less line losses

Calculations are the same as the previous point but with the values from Östersund. A plot of the current can help to understand better the results

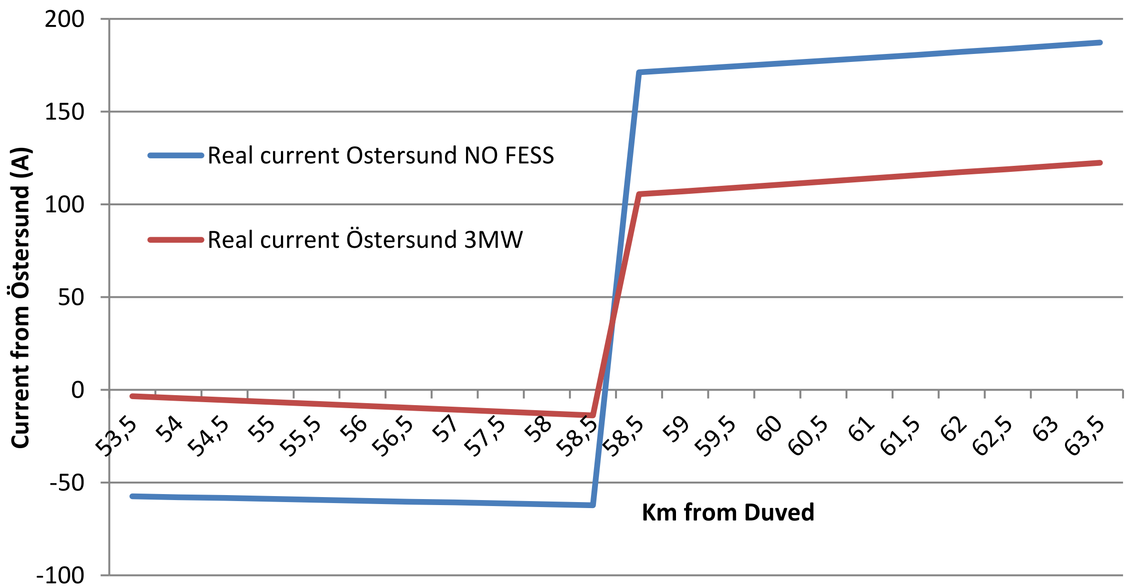

Figure 41 Current from Östersund when the train is moving

Energy savings= $8.19\cdot10^7$ J = 22.75 kWh

3- **Line losses from FESS to the train:**

This value quantifies the energy losses due to the power flow between the train and the FESS.

$$Energy\ savings = \sum_{i=53.5}^{58.5} r \cdot (58.5 - \mathrm{i}) \cdot (If_i)^2 \cdot \mathrm{t_i} + \sum_{i=58.5}^{63.5} \mathrm{r} \cdot (58.5 - \mathrm{x}) \cdot (If_i)^2 \cdot \mathrm{t_i}$$

The plot of the current is:

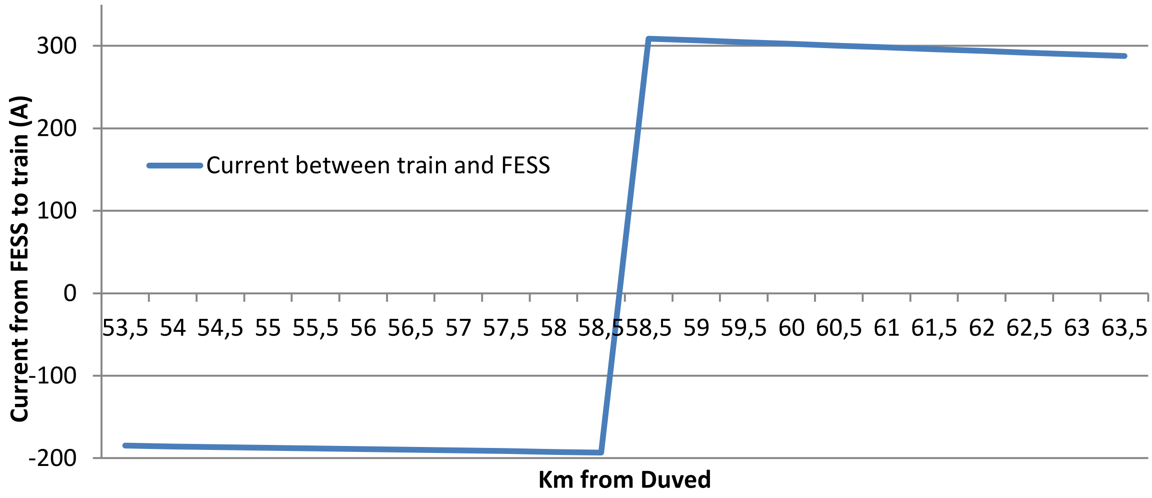

Figure 42 Current from FESS to train

Note: Negative currents means that the current is flowing from the train to the FESS (in regenerative mode).

Energy savings= -9.35 ·10^5 = -0, 26 kWh

4- **Energy savings from Duved in less Energy delivered**

The following number is obtained by multiplying the difference of the current in both cases and the voltage value of the power supply.

$$Energy\ savings = \sum_{i=53.5}^{63.5} 16500 \cdot (\mathrm{Id_i} - Idf_i) \cdot \mathrm{t_i}\ = 1.57 \cdot 10^8 \mathrm{J} = 43.50\ \mathrm{kWh}$$

5- **Energy savings from Östersund in less Energy delivered.**

The following number is obtained by multiplying the difference of the current in both situations and the voltage value of the power supply.

$$Energy\ savings = \sum_{i=53.5}^{63.5} 16500\ [V] \cdot (\mathrm{Id_i} - Idf_i) \cdot \mathrm{t_i}\ = 1.46 \cdot 10^8 \mathrm{J} = 40.50\ \mathrm{kWh}$$

Total energy savings per trip:

$$Total\ energy\ savings = 19.99 + 22.75 - 0.26 + 43.50 + 40.50 = \ 121.87\ \text{kWh}$$

The process is repeated for a capacity of 1.4MW and 4.2MW. The results are:

$$Total\ energy\ savings\ for\ 1.34\ MW\ = 98.76\ kWh$$

$$Total\ energy\ savings\ for\ 4.2\ MW\ = \ 108.54\ kWh$$

Payback time

Assumptions:

The installation of the FESS will offer a power charge and discharge delivered over 200s (0.055h). With the assumption of 150US$/KW installation costs

$$Corrected\ cost\ \frac{US\$}{KW} = Energy\ \left(\frac{US\$}{KWh}\right) \cdot 0.055\left(\frac{KWh}{KW}\right) + \text{Power}\left(\frac{US\$}{KW}\right) + Installation(\frac{US\$}{KW})$$

Corrected cost = 675US$/KW

An installation of:

- 3MW will cost 2.025M$ and will be able to store 166.67KWh
- 1.34 MW will cost will cost 0.904 M$ and will be able to store 74.44KWh
- 4.2 MW will cost 2.835M$ and will be able to store 233KWh

Interest rate is fixed to 0.75% according actual regulations

Energy tariff is fixed to 75öre/kWh (0.11 US $/kWh), according Trafikverket.

The payback time will be function of the number of trips per day. Considering 25 trips per day, the payback time is:

Table 13 Payback time, case 2

	FESS Power [MW]		
	1.34	**3**	**4.2**
Payback time [years]	8	15	23

The FESS with les power is the one that shows a Payback time smaller.

6- FESS for weak power lines

Description

Investment on FESS will worth especially for those lines with big resistance and when two concurrent traction stations are rather separate from each other, so when the train is moving in between, losses in the line and voltage drop will appear, growing if the train is requesting more power (e.g. the train is accelerating or is driving uphill). A solution placing a FESS in between the traction stations will allow the train be supplied from a closer power supply (if the flywheel is charged) and handling with the voltage drop. Since power losses in the lines is proportional to the square of the current, charging the flywheel at slow current rate and deliver the energy when the train is nearby the flywheel, will save some energy than, instead, power the trains from the traction stations. Energy savings and increase of performance have been the motivation for the investment. This solution is an alternative to increase the section of the power lines.

Aiming

The aiming of this section is:

- To compare the performance of the power system when incorporating a FESS by displaying overhead line voltage and current distribution.
- To quantify energy savings when integrating a FESS in the power system and the payback time of the investment

Requirements and assumptions

1- Data of the line

Studying the Swedish network, one possible case has been developed, the line in between Duved and Östersund, figure 21.

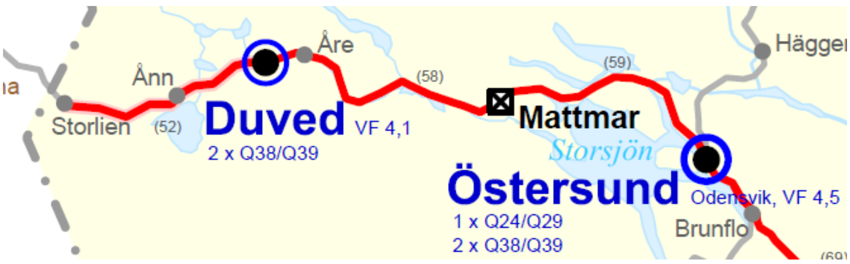

Figure 43 Östersund-Duved line in a Sweden map

Length: 117 Km

Return line: Booster Transformer system (BT-system)

Line impedance, single track lines [Ohms/Km]: Typical value: 0.28 + j 0.23

From the current situation, the suggestion is to place a FESS in Mattmar segmentation station, since is placed in between the traction station and the existing installation will make it easier to retrofit with a FESS.

2- Range of operation

FESS will be installed in Mattmar station, since the aiming is to deliver energy close to the trains, the discharge of the flywheel will be done nearby Mattmar, i.e., the range of operation will be around 10 km before and after the train reach Mattmar. Detailed numbers will be displayed later.

3- Load of the train

In order to make calculations simple, trains will be considered as a constant load all across the range of operation of the FESS.

4- Power and energy proposed for FESS

The following active and reactive power delivered by the FESS, will be the starting point in order to dimension the FESS

500KWh, 3MW, 0MVar, 10 minutes discharge
500KWh, 3MW, 0.5MVar, 10 minutes discharge

6.1 Iterative calculations

A simple model of the network has been created, where the traction stations are represented as a power supply constant to 16500 V. The FESS is charged from Duved and Östersund (both can deliver the same amount of energy since the FESS will be placed in the middle), during 60 minutes (constant angular acceleration to 0,7rad/s^2 up to 20.000 rpm). The restriction comes that in the range of 5 min before and after the train reaches the position where the flywheel is, this one will have prioritization in front any power source. The flywheel can supply 10min=600s x 3MW = 1800MJ = 500KWh (for the 3MW, 500kWh FESS)

Model (When the train is at x Km from Duved station):

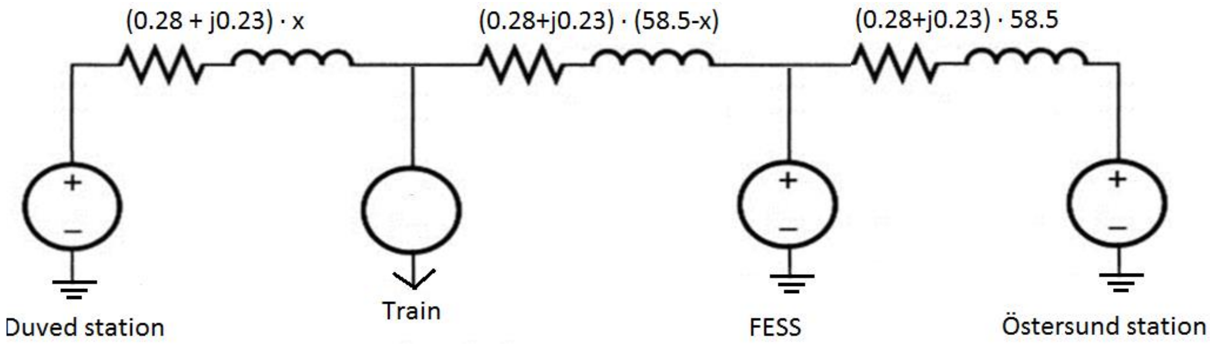

Figure 44 Power system model when train is at x km from Duved Station

In this case, a freight train, 5.6MW is moving near Mattmar station. Power losses and voltage drop will be compared by studying the case incorporating a flywheel in Mattmar station and without it. The power of the train is fixed to 4.2MW (75% of the maximum) and a reactive power of 0.5MVar

The equation of the system has been solved with the following considerations:

- Power supply at Duved is considered as 16500V constant, at 0 phase.
- Power supply at Östersund is considered as 16500V constant, at 0 phase, so both stations are in phase.
- Internal resistance in the station is neglected
- Line resistance is 0,28+j0,23 Ohms/Km.
- Variables to change are active power consumed for the train, *P*, reactive power consumed by the train, *Q*. And the distance the train is from Duved, *Km*.

Equations to solve are displayed in Appendix B, which results in 4 equations for 4 unknown variables; these are the real and complex values for the current coming from Duved and Östersund.

When the FESS is included, the active and reactive power that this one is giving is fixed. Then, the system is described by 6 equations, with 6 unknown variables, the real and imaginary part of the current coming from one traction station and the FESS, and the real and imaginary values of the voltage at the FESS point. Equations displayed in Appendix B as well

Mattmar station, i.e., where the FESS is installed is placed at 58,5Km from Duved Station, instead of 58Km which is the real position. In such a way, the FESS is placed exactly in between Duved and Östersund. Since the model for the power supply placed at Östersund and Duved is exactly the same, results will be symmetric from both sides of the length of the track. In the following graphs, the results will show the values of current and voltage from 0 to 58.5 Km from Duved. In figure 23, there is a comparison on the overhead line voltage for a power system with a FESS that delivers 3MW and 0,5MVAr (purple line), a FESS that delivers 3MW and 0MVAr (green line) during 5 minutes (around 8Km). Along these 5 minutes a freight train is passing, requesting a constant load of 4,2MW and 0,5MVar.

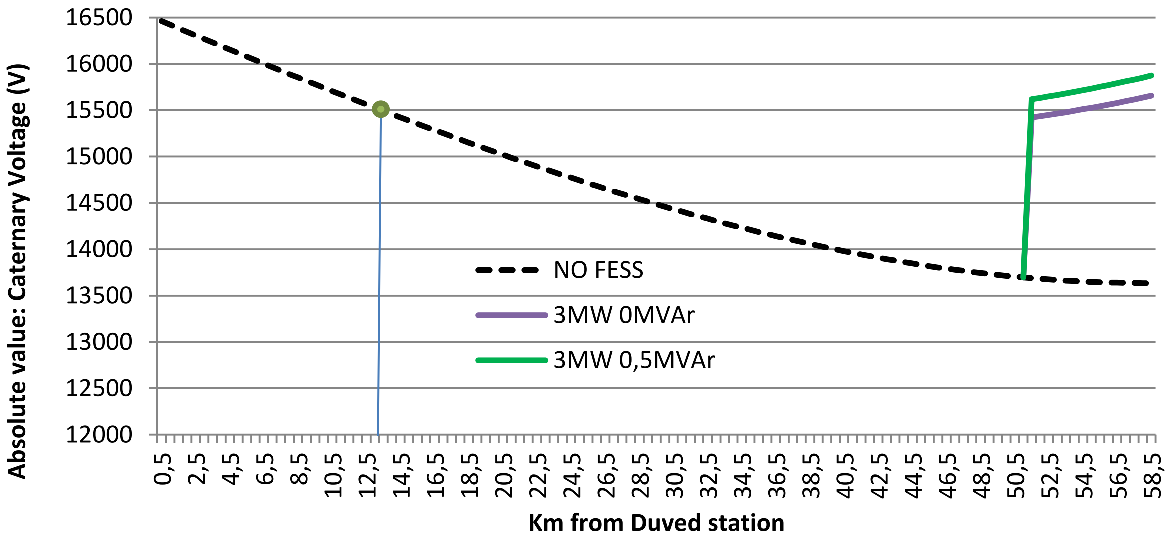

Figure 45 Catenary voltage for different train location

The dotted black line corresponds to the overhead line voltage in a power system without FESS in each point of the track, considering that there is a freight train requesting a constant load of 4,2MW and 0,5MVAr all the time. So, if a train like that is at 13Km from Duved the overhead line voltage is 15500V (green point). In a real scenario, this train will not request the same power along the 117km of track but it is displayed in order to compare it with the other two lines.

Power quality improvements

The previous graph shows how the overhead line voltage is raised by the incorporation of a FESS, during these 10 minutes when the FESS is delivering energy.

Maximum and minimum voltage boost (%)

Minimum

Without FESS: Reference

With FESS, 3MW 0 MVAr: (15422.1-13688.9)/ 13688.9 = **12.66%**

With FESS, 3MW, 0.5 MVAr: (15618.5-13688.9)/ 13688.9= **14.10%**

Maximum

Without FESS: Reference

With FESS, 3MW 0 MVAr: (15655.4-13635.1)/ 13635.1= **14.82%**

With FESS, 3MW, 0.5 MVAr: (15873-13635.1)/ 13635.1= **16.41%**

From the following figures, the values for the currents are displayed:

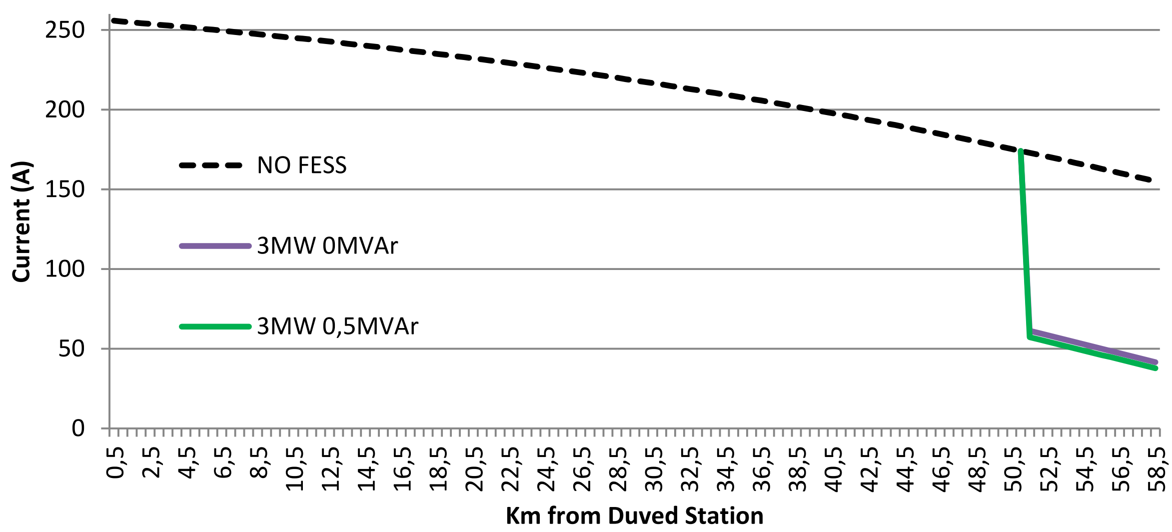

Figure 46 Absolute current from Duved Station

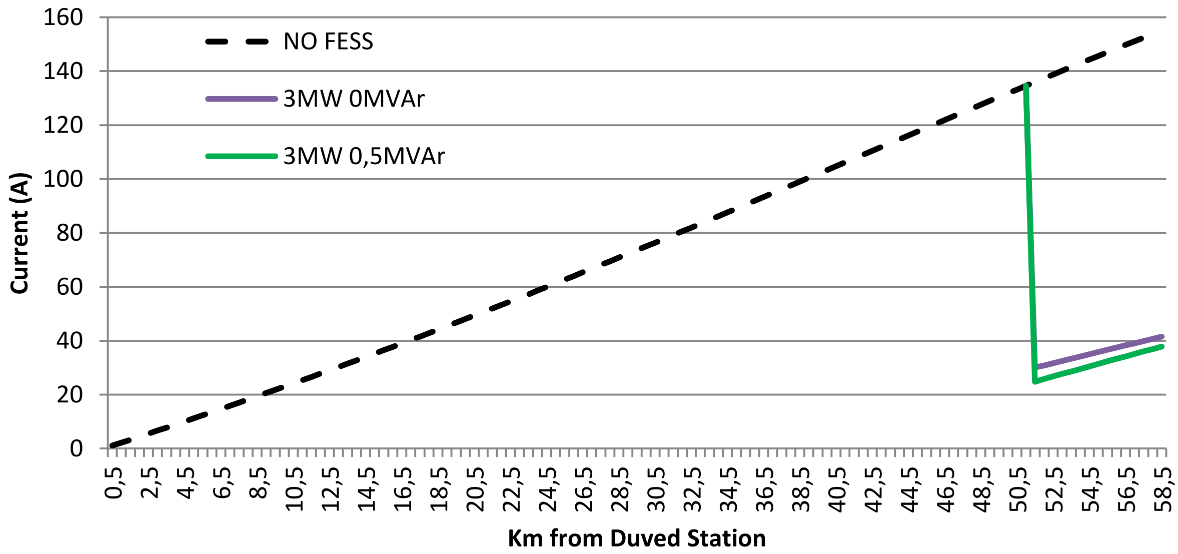

Figure 47 Absolute current from Östersund

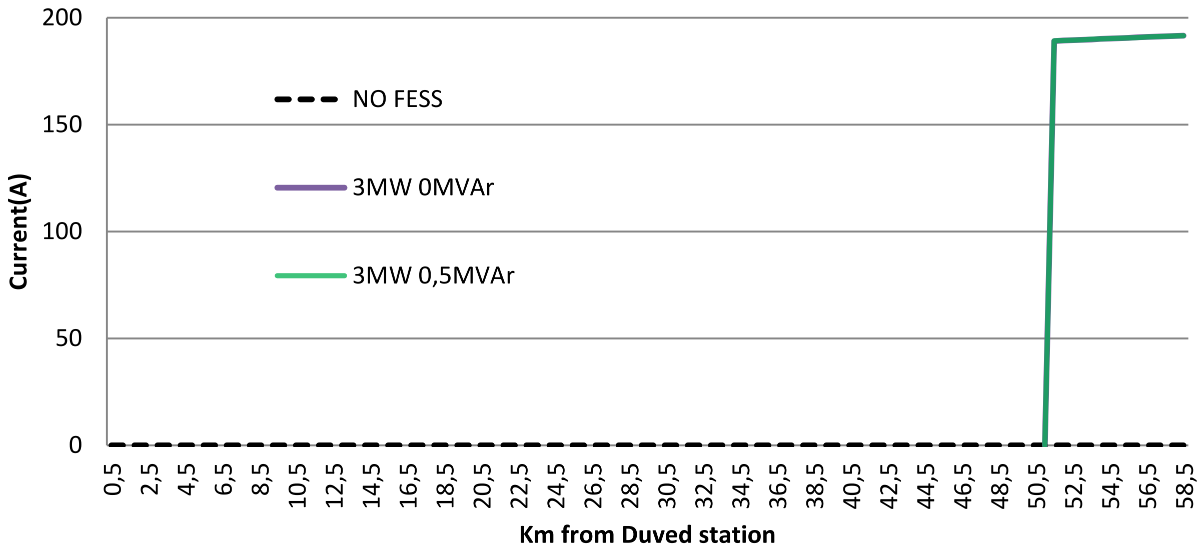

Figure 48 Absolute current from FESS

Further Calculations:

The next iterations of calculations will consider:

- A reduced power delivered by the FESS based on the economic evaluation of the first iteration, with a discharge time of 20 minutes

2nd iteration

Similarly than the first iteration but now the power given for the flywheel is:

1.5MW 0MVAr or 1.5MW 0.5MVAr, 500KWh, 20minutes discharge.

In the following graphs is displayed the new lines with the previous ones as well, in order to compare them

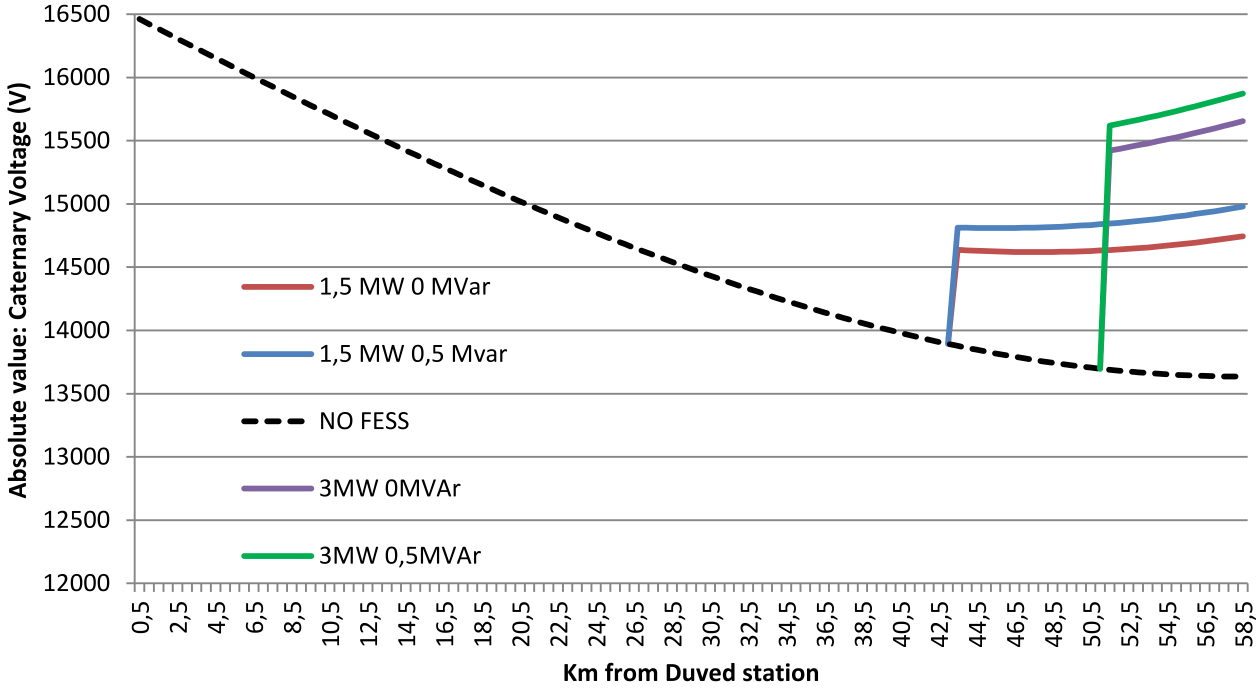

Figure 49 Catenary voltage for different train location

Maximum and minimum voltage boost (%)

<u>Minimum</u>

Without FESS: Reference

With FESS, 1MW, 0 MVAr: (14637-13877.4)/ 13877.4= **5.47%**

With FESS, 1MW, 0.5 MVAr: (14813.3-13877.4)/ 13877.4= **6.74%**

With FESS, 3MW 0 MVAr: (15422.1-13688.9)/ 13688.9 = **12.66%**

With FESS, 3MW, 0.5 MVAr: (15618.5-13688.9)/ 13688.9= **14.10%**

Maximum

Without FESS: Reference

With FESS, 1MW, 0 MVAr: (14744.5-13635.1)/ 13635.1= **8.14%**

With FESS, 1MW, 0.5 MVAr: (14979.1-13635.1)/ 13635.1= **9.86%**

With FESS, 3MW 0 MVAr: (15655.4-13635.1)/ 13635.1= **14.82%**

With FESS, 3MW, 0.5 MVAr: (15873-13635.1)/ 13635.1= **16.41%**

Current distribution:

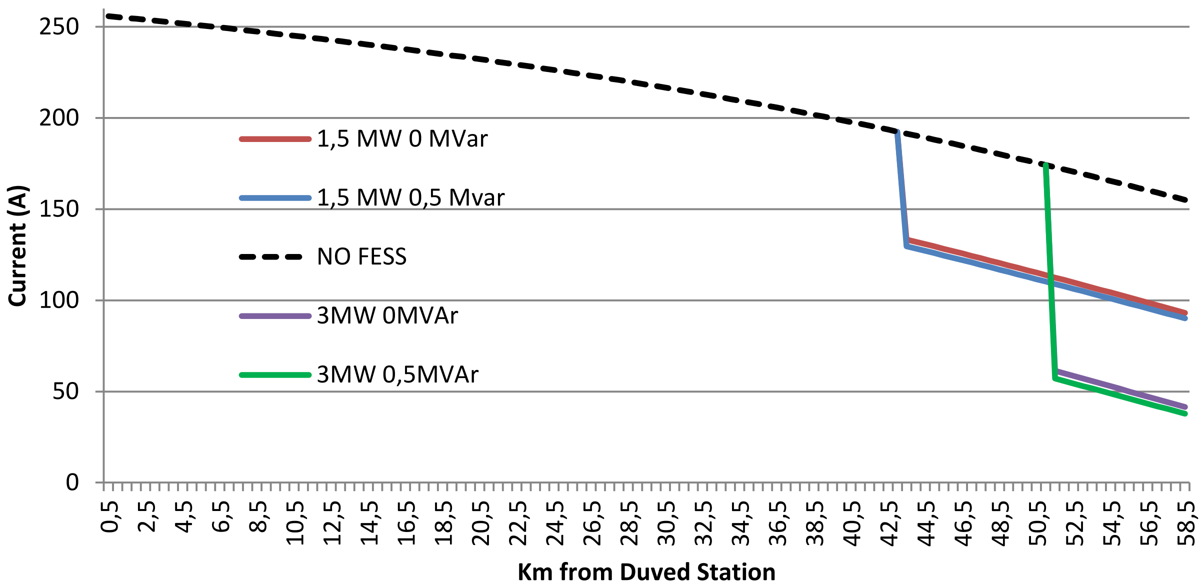

Figure 50 Absolute current from Duved Station

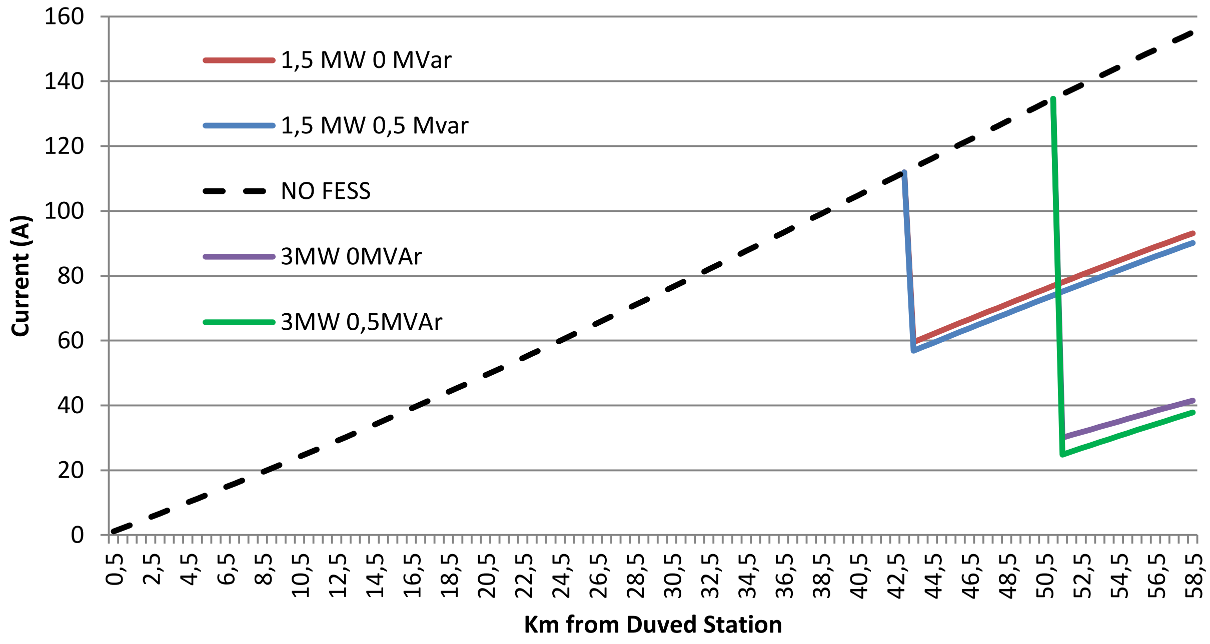

Figure 51 Absolute current from Östersund

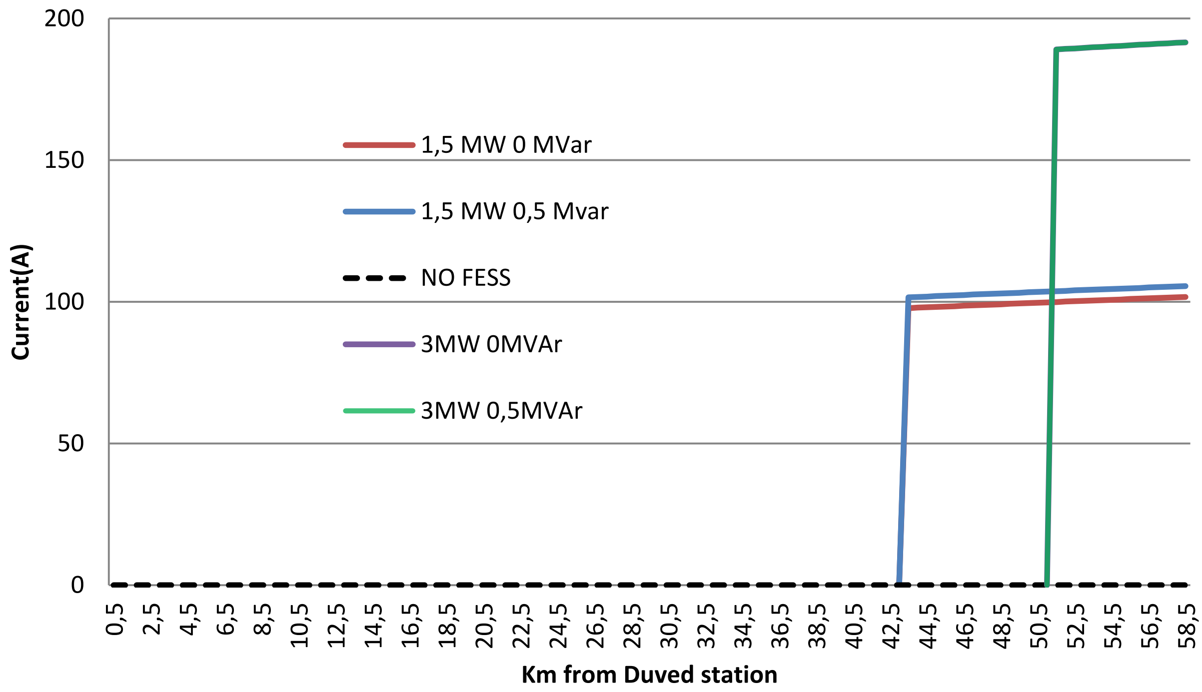

Figure 52 Absolute current from FESS

6.2 Economic evaluation

When evaluating the results we must consider the difference between the initial power system without FESS, set as a reference and the system that includes the FESS

1- Energy savings from Duved due to less line losses: Current values are low with FESS
2- Energy savings from Östersund due to less line losses: Current values are low with FESS
3- Line losses from FESS to the train: Since in the reference case it doesn´t exist
4- Energy savings from Duved in less Energy delivered during the discharge of the FESS
5- Energy savings from Östersund in less Energy delivered during the discharge of the FESS
6- Energy needed to charge FESS including line losses.

For the first iteration, it is obtained the energy savings (in KWh) for every single point described above. These values are only the half of the total value as explained previously:

Table 14 Energy savings separate by points, first iteration

	3MW 0MVAr	3MW 0.5MVAr
1	+16.2	+16.3
2	+17.6	+17.7
3	-2.9	-2.8
4	+154.3	+155.0
5	+151.7	+152.0
6	-257.5	-257.1
Total*2	**158.5**	**162.2**

With the assumption of 1100US$/KW (this is the number calculated in the section 2.1 plus and additional 150US$/KW on installation costs. A 3MW installation will cost 3.3M$ and will be able to store 500KWh.

Interest rate is fixed to 0.75% according actual regulations

Energy tariff is fixed to 75öre/kWh (0.11 US $/kWh), according Trafikverket.

The payback time will be function of the number of trips per day. Considering 25 trips per day, the payback time is:

Table 15 Payback time, first iteration, case 3

	FESS Power	
	3MW 0MVAr	**3MW 0.5MVAr**
Payback time [years]	15	15

For the second iteration, it is obtained the energy savings (in KWh) for every single point described above. These values are only the half of the total value as explained previously:

Table 16 Energy savings separate by points, second iteration

	1.5MW 0MVAr	1.5MW 0.5MVAr
1	+14.9	+15.2
2	+7.6	+7.6
3	-2.6	-2.4
4	+208.2	+210.6
5	+93.0	+93.2
6	-257.1	-256.9
Total*2	**128**	**134,6**

Now, the cost per kW will be:

$$Corrected\ cost\ \frac{US\$}{KW} = Energy\left(\frac{US\$}{KWh}\right) \cdot 0.33\left(\frac{KWh}{KW}\right) + \text{Power}\left(\frac{US\$}{KW}\right) + Installation(\frac{US\$}{KW})$$

Corrected cost = 1750US$/KW

A installation of 1.5MW will cost 2.675M$ and will be able to store 500KWh

Interest rate is fixed to 0.75% according actual regulations

Energy tariff is fixed to 75öre/kWh (0.11 US $/kWh), according Trafikverket.

The payback time will be function of the number of trips per day. Considering 25 trips per day, the payback time is:

Table 17 Payback time, second iteration, case 3

	FESS Power	
	1.5MW 0MVAr	**1.5MW 0.5MVAr**
Payback time [years]	15	15

The calculations will stop here, for two different values; the payback time is approximately the same. The reason is that for a longer discharge time the corrected cost is bigger and despite the installation has to be smaller, to energy savings are less as well.

7- Discussion

In this chapter, the aiming is to discuss, compare and evaluate the theory and literature review with the findings of this thesis.

The discussion in section 2.1 has started previously: What literature offers is on one hand a power and energy cost for each energy storage technology and on the other hand energy and power densities. In order to know which technology is cheaper, the author based their calculations on discharge time target, considering oversizing costs for those technologies that are not in the optimal position, a 970 US$/KW for a 10 minutes discharge time flywheel and 370 US$/KW for a 1 minute discharge time was estimated. Discussion with one of the flywheel manufacturers has been conducted along the thesis, they provided the equipment cost per kW as well, being around 700-900 US$/KW for 264kW, 5 minutes discharge time unit and around 600-750 US$/KW for a 400kW, 1 minute discharge time unit. An estimation installation cost of 220-400 US$/kW including shipping is estimated. Those values are more expensive than the ones calculated in the report, particularly for a 1 minute discharge time: A mismatch of the manufacturer data and literature data is detected, however, manufacturers usually offers discounts for large installations alike technical support and knowledge that can be considered in the cost. Furthermore, installation costs for transformers or power electronics are difficult to calculate since it depends on the electrification system flywheels will be incorporated.

From 2.2, the parameters that affects the energy stored in a flywheel are explained, such material properties and geometry. Applications where neither mass nor volume is relevant, material decision is based on its tangential stress, instead of tangential stress over density. This conclusion reduces the potential advantages of high strength, light-weight graphite fibre over conventional steel flywheel.

In Section 2.3 it is compared steel versus GFRE flywheel with the same rotor shape and results seems obvious: GFRE offers better performance at the expense of a higher cost. However, two considerations when selecting the material must be taken: the cost and type of the bearings that will spin the flywheel. Despite high reliability of ball bearings, reduced cost, easy maintenance and not electronic control at all, active magnetic bearings are preferred according current flywheel manufacturers for its performance and high-speeds achieved.

As explained in section 2.4 the first flywheel designers rely on weight to have more energy stored for a low-speed flywheels, then they moved into high-speed, low-weight flywheels since the energy stored is proportional to the square of rotational speed. Finally, the combination of high-speed and heavy flywheel is defined as a third generation flywheel. Despite this trend is being achieved due to technological advances; current manufactures do not aim for a single big unit but a multiple small units, being the second generation the most common one.

PMSM and SRM are generally used as a motor/generator to power FESS and the motivation is mainly based on an overall high efficiency and low rotor losses. The control of these machines is a requirement that the designer must consider, not considered in this thesis due to a high dependence of the system parameters.

As it can be seen in subsection 2.6 there are some FESS prototypes designed for railway application that are not integrated in the railway network. Others, instead, are incorporated but at metro/tramway scale, no FESS retrofit railway power systems for trains and locomotives. This fact can be seen as a potential risk for new investments or as an opportunity to extend their use at a larger scale.

Most of the flywheel suppliers focus their application for Uninterruptible Power Supply (UPS), being the energy stored very low, and discharge time not enough for railway application. However, Beacon Power offers a wide range of discharge time for their flywheels. A recommendation to future investors would be to look into that company, since different configurations for FESS can be chosen, as seen in section 2.7.

The features of a Beacon Power flywheel are listed below:

Beacon Power	
Flywheel generation	Second
Power (KW)	50-190
Energy (KWh)	~30
Max speed (rpm)	15500
Material	Carbon fibre and fiberglass
Type of bearings	Magnetic
Motor/Generator	PMSM
Efficiency	~85%

Table 18 Features for one of Beacon Power flywheels

Despite in this thesis the application is considered to be fixed at one place, not on-board any vehicle, moving the flywheel assembly is not difficult. The suppliers like to call it “dig and rig”: A hole is dug in the ground and the flywheel foundations sits in the whole, is levelled, and then surrounded by gravel. The flywheel is bolted to the base of the concrete foundation and a cover is placed over it. Whether or not it is wanted to dig up the foundations is an economic and future planning question, since it might be necessary to move the flywheels back at some point. Then if flywheels are needed in other places, it must be unbolted from the foundation and moved to the desired place together with the power electronics package.

The flywheel assembly, without considering the foundation, measures 200cm height for 120cm in diameter. Power control module is a box that measures 100 x 100 x 150cm.

To have a better overview of how the system can look like, a 14 flywheel installation, with a range of power between 700 to 2660 kW depending of the flywheel configuration is showed below, the space occupied is around 20m long 10 m wide:

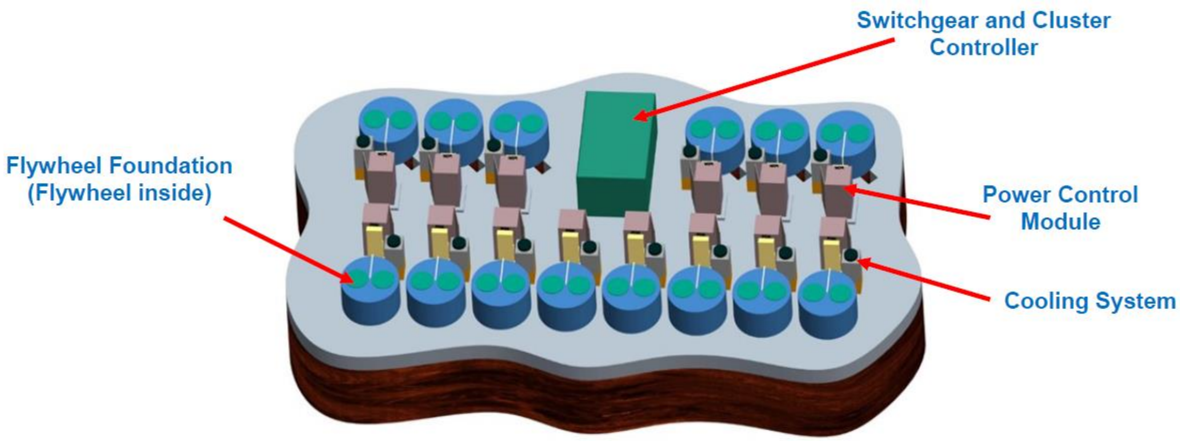

Figure 53 Installation of 14 flywheels.

8- Conclusions

In chapter 4, a 3MW capacity FESS will lead to a peak reduction loads in the rotary converters of the same value. Moreover, by incorporating an energy storage device the power capacity requested to the energy supplier is reduced up to 5.8 MVA, entailing up to 209902 US$ savings per year. A proper strategy to control the SOC of the FESS will mean a minimum energy capacity for the device and as a consequence a reduced installation costs. Loads can be predicted based on the position and dimension of trains, then for a 1500 MJ (416.67 KWh) minimum energy capacity, the payback time of the installation is 14 years. FESS can be a solution when more power is requested for a traction station and cannot be given from the national grid because difficulties on access or power plants are far away. This solution supports current stations giving more flexibility and independence since one of the converters can be omitted or used as a back-up in case of failure of the other one.

In chapter 5, the key feature of energy storage is displayed, a FESS that is able to be charged from the regenerative braking of trains and discharged when the train request energy, supplying it closer to the loads and far from any traction station. A 1.34 MW capacity with a 200 s discharge time allows the complete recovery of braking energy within overhead line voltage regulations. Power limitation is increased from 70% in a system without FESS to 85%. Energy saving per trip is more than 98 kWh, which leads to a payback time of 8 years. Despite the performance is highly dependent on the geographical situation, a value of 1.34 MW ensures a total energy recovery for slopes up to 2%. In this study, it is proven the utility of FESS installed in regular passenger station where these units can absorb the regenerative braking when the train stops to pick up passengers and use that energy to boost the catenary voltage when the train is accelerating. This potential advantage can be used in the chapter 4 scenario as well, with energy savings up to 30 kWh

In chapter 6 it is seen than a 3MW capacity FESS is able to increase the overhead line voltage up to 16.41% and achieve more than 160 kWh energy savings per trip compared with a system without FESS. An installation of this capacity will request a payback time of 15 years at least. Calculations show that energy savings are bigger when FESS is delivering not only active power but reactive power in the same magnitude than the train is requesting it. Reactive power supplied from FESS has to be close to trains request in order to maximize savings and increase overhead line voltage. A same energy capacity FESS, 500kWh, with 1.5MW maximum power output show a 15 year payback time as well. As longer the discharge time is, more expensive is the installation cost for this technology, but fewer the power capacity installed, cheaper the installation costs. FESS not only will provide energy savings but an increase of performance when train loads are more than 4.2MW for a single train travelling in between two traction stations separate 120 Km.

A table-summary is exposed below with the three scenarios studied:

	FESS to reduce peak power	FESS to be charged with regenerative braking	FESS for weak power lines
FESS Capacity (MW)	3	1.34	From 1.5 to 3
FESS Energy (KWh)	416	74.4	500
Discharge time (minutes)	10	3.33	From 20 to 10
Peak power reduction	3MW	N/A	N/A
Energy savings per trip (kWh)	30	98	160
Increase of Performance	5.8 MVA power capacity reduction	Power limitation from 70 to 85%	16.41% voltage boost – 2200V
Payback time [years]	14	8	15

An incentive to explore and study FESS is that power and energy costs for this technology will decrease in the future and, at the same time, electricity cost will increase, becoming cost energy savings bigger. Moreover, for an increase of power of trains and locomotives, the power lines will not be a limiting factor if FESS is integrated in the power system.

Beyond the previous numbers, there is a list of applications where FESS can be used:

- The depth of discharge and the frequent charge and discharge cycles is not affordable for batteries without oversizing them, even more than calculated in previous sections where energy and power density requirements were the only parameters considered when comparing technologies. There, Ld-Acid batteries were a competitor, however after developing the study it is seen that batteries will not be a good option to reduce power peaks in the traction stations.
- FESS can be used when replacing old converters, replacing them for a combination of a converter plus flywheel, instead of a bigger converter, in that way, for a similar investment cost, energy savings and increase of performance is achieved.
- FESS can be used as well as a back-up system when a converter needs maintenance or is damaged for a long time. If the FESS can move from one place to other, the same system can be useful in different stations.

- FESS can be used as a solution to provide the extra amount of power required for a station that will handle an increase of the frequency of trains, instead of adding a new converter.

9- Future research

In this section it will be presented in which way this research can be improved and studied in more detail based on the experience and knowledge acquired after the realization of the thesis.

A suggestion from the author is to use railway power systems simulation tools to carry out simulations for more precise results: Open Power Net, SIMPOW®, and TRACFEED® are some recommendations. The first step could be to include a one-day continuous simulation considering all the trains that are moving between two traction station, where two, three or even four trains are moving between two traction stations at the same time. This situation will lead to critical values of overhead line voltage and bigger line losses, so incorporating a FESS will be much more advantageous, and at the same time the scenario studied will be more close to the reality.

A detailed explanation of the control strategy for charging and discharging the flywheel system can be included to minimize the energy stored in the flywheel. FESS will provide power peaks but it has to work together with the already implemented converters in the traction stations, so the assembly must have a control strategy to maximize the advantage of a FESS.

For big installations it may worth a combination of different technologies, using the high power density of supercapacitors or the high energy density of batteries, together known as hybrid systems. Proper integration can lead to better performance by the expense of the knowledge needed to integrate more than one system for a single application, since the company must deal with the disadvantages of all technologies, like different maintenance, range of operations and requirements.

For large investments, it might worth an installation of a wind turbine to: charge FESS at reduced cost and keep the system more independent of the national grid. With such big energy storage, irregular wind velocity is solved with energy management. Electricity cost will increase in the future and green alternatives will be financed and supported.

List of figures

List of tables

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Appendix A

Train parameters

185/241/El19/Re Freight train from Bombardier

The trains used in the calculations are intended to be a typical freight train in Sweden, consisting of a single locomotive of 5.6 MW and 36 two-axle cars, giving a total train mass of 1000 t. The cars are a mix of open and closed cars. A real train would normally consist of a mix of 2, 4 and 6-axle cars, but the total number of axles is realistic. Train data is given in table 17, obtained from [27].

Table 19 Train data

Parameter	Unit	Value
Train mass	t	1000
Dynamic mass[4]	t	1054.2
Total Length	m	500
A [5]	kN	12.07
B [5]	kN/(km/h)	$7.722 \cdot 10^{-2}$
C [5]	kN(Km/h)^2	$3.735 \cdot 10^{-3}$
Locomotive mass (adhesion mass)	t	84
Rated mechanical power	MW	5.6
Rated electrical power for traction	MW	6.364
Efficiency [6] **(lower at speed below 40 km/h)**	1	0.88
Auxiliary electrical power and no –load losses	kW	123.5
Max tractive effort	kN	300
Max electric braking effort	kN	240

[4] Dynamic mass is locomotive mass · 1.1 + cars' mass · 1.05.

[5] A, B and C are constants describing the train's driving resistance, $F_R = A + B \cdot v + C \cdot v^2$. F_R is driving resistance in kN, v is speed in km/h.

[6] Efficiency does not include auxiliary power

Appendix B

In this Appendix, it will be displayed all the equations used to solve the power flow problem for each section:

Section 4.1 – First iteration

3MW, 500kWh without FESS

```
F= [Vduved*x(1)-(Km)*0.28*(x(1)^2+x(2)^2)-P+Vost*x(3)-(KmtoOst)*0.28*(x(3)^2+x(4)^2);
    -Vduved*x(2)-(Km)*0.23*(x(1)^2+x(2)^2)-Q-Vost*x(4)-(KmtoOst)*0.23*(x(3)^2+x(4)^2);
    (Km)*0.28*x(1)-(Km)*0.23*x(2)-(KmtoOst)*0.28*x(3)+(KmtoOst)*0.23*x(4);
    (Km)*0.28*x(2)+(Km)*0.23*x(1)-(KmtoOst)*0.28*x(4)-(KmtoOst)*0.23*x(3)];
```

Current Duved = x(1) +jx(2)

Current Östersund = x(3) + j(4).

3MW, 500kWh with FESS

```
F= [Vduved*x(1)-Km*0.28*(x(1)^2+x(2)^2)-P+(x(5)*x(3)+x(4)*x(6))-(KmtoFly)*0.28*(x(3)^2+x(4)^2);
    -Vduved*x(2)-Km*0.23*(x(1)^2+x(2)^2)-Q-x(5)*x(4)+x(3)*x(6)-(KmtoFly)*0.23*(x(3)^2+x(4)^2);
    16500-Km*0.28*x(1)+(Km)*0.23*x(2)-x(5)+(KmtoFly)*0.28*x(3)-(KmtoFly)*0.23*x(4);
    0-(Km)*0.28*x(2)-(Km)*0.23*x(1)-x(6)+(KmtoFly)*0.28*x(4)+(KmtoFly)*0.23*x(3);
    Pf-x(5)*x(3)-x(4)*x(6)];
   -Qf-x(5)*x(4)+x(3)*x(6);
```

Current Duved = x(1) +jx(2)

Current Östersund = x(3) + j(4).

Current Flywheel = x(5) + j(6).

Section 5.1

In order to clarify the direction of the signals; when talking about current, the word “from” means that the current is going for the load/power supply to the system. The work “to” means that the system is feeding the load/power supply. Voltages are always referred to ground. Respect

1st iteration

Downhill, no FESS

Current from Duved: x(1) + jx(2)

Current from Östersund: x(3) + jx(4)

Current to the train: x(5) + jx(6)

Voltage of the train: x(7) + jx(8)

Active power train: Pt

Reactive power train: Qt

Line resistance: r

Line inductance: l

```
Qt=0;

Pt=-3460000;

r=0.28;

l=0.23;

F= [16500*x(1)+16500*x(3)-Pt-r*(km*(x(1)^2+x(2)^2)+(117-km)*(x(3)^2+x(4)^2));

    -16500*x(2)-16500*x(4)-Qt-l*(km*(x(1)^2+x(2)^2)+(117-km)*(x(3)^2+x(4)^2));

     x(7)*x(5)+x(8)*x(6)-Pt;

    x(8)*x(5)-x(7)*x(6)-Qt;

   16500-km*(r*x(1)-l*x(2))-x(7);

   -km*(r*x(2)+l*x(1))-x(8);

   16500-(117-km)*(r*x(3)-l*x(4))-x(7);

   -(117-km)*(l*x(3)+r*x(4))-x(8)];
```

Uphill, no FESS

Current from Duved: x(1) + jx(2)

Current from Östersund: x(3) + jx(4)

Current to the train: x(5) + jx(6)

Voltage of the train: x(7) + jx(8)

Active power train: x(9)

Reactive power train: Qt

Line resistance: r

Line inductance: l

```
Qt=0;

r=0.28;

l=0.23;

 F= [16500*x(1)+16500*x(3)-x(9)-r*(km*(x(1)^2+x(2)^2)+(117-km)*(x(3)^2+x(4)^2));

   -16500*x(2)-16500*x(4)-Qt-l*(km*(x(1)^2+x(2)^2)+(117-km)*(x(3)^2+x(4)^2));

   x(7)*x(5)+x(8)*x(6)-x(9);

   x(8)*x(5)-x(7)*x(6)-Qt;

   35.36*x(9)-x(7)^2-x(8)^2;

   16500-km*(r*x(1)-l*x(2))-x(7);

   -km*(r*x(2)+l*x(1))-x(8);

   16500-(117-km)*(r*x(3)-l*x(4))-x(7);

   -(117-km)*(l*x(3)+r*x(4))-x(8)];
```

Downhill, with FESS

Current from Duved: x(1) + jx(2)

Current from Östersund: x(3) + jx(4)

Line current between FESS and train: x(5) + jx(6)

Voltage of the train: x(7) + jx(8)

Voltage of FESS: x(9) + jx(10)

```
Pt=-3460000;

Qt=0;

Pf=-3000000;

Qf=0;

 r=0.28;

l=0.23;

 F=[16500*x(1)+16500*x(3)-Pt+Pf-r*(km*(x(1)^2+x(2)^2)+(58.5km)*(x(5)^2+x(6)^2)+(58.5)*(x(3)^2+x(4)^2));

   -16500*x(2)-16500*x(4)-Qt+Qf-l*(km*(x(1)^2+x(2)^2)+(58.5-km)*(x(5)^2+x(6)^2)+(58.5)*(x(3)^2+x(4)^2));

   x(7)*(x(1)+x(5))+x(8)*(x(2)+x(6))-Pt;

   x(8)*(x(1)+x(5))-x(7)*(x(6)+x(2))-Qt;

   x(9)*(x(5)-x(3))+x(10)*(x(6)-x(4))-Pf;

   x(10)*(x(5)-x(3))-x(9)*(x(6)-x(4))-Qf;

   16500-km*(r*x(1)-l*x(2))-x(7);

   -km*(r*x(2)+l*x(1))-x(8);

   16500-(58.5)*(r*x(3)-l*x(4))-x(9);

   -(58.5)*(l*x(3)+r*x(4))-x(10)];
```

Uphill, FESS

Current from Duved: x(1) + jx(2)

Current from Östersund: x(3) + jx(4)

Line current between FESS and train: x(5) + jx(6)

Voltage of the train: x(7) + jx(8)

Voltage of FESS: x(9) + jx(10)

```
Qt=0;
Pf=3000000;
Qf=0;
 r=0.28;
l=0.23;
 F=
[16500*x(1)+16500*x(3)-x(11)+Pf-r*(km*(x(1)^2+x(2)^2)+(58.5-km)*(x(5)^2+x(6)^2)+(58.5)*(x(3)^2+x(4)^2));
   -16500*x(2)-16500*x(4)-Qt+Qf-l*(km*(x(1)^2+x(2)^2)+(58.5-km)*(x(5)^2+x(6)^2)+(58.5)*(x(3)^2+x(4)^2));
   x(7)*(x(1)+x(5))+x(8)*(x(2)+x(6))-x(11);
   35.36*x(11)-x(7)^2-x(8)^2;
   x(8)*(x(1)+x(5))-x(7)*(x(6)+x(2))-Qt;
   x(9)*(x(5)-x(3))+x(10)*(x(6)-x(4))-Pf;
   x(10)*(x(5)-x(3))-x(9)*(x(6)-x(4))-Qf;
   16500-km*(r*x(1)-l*x(2))-x(7);
   -km*(r*x(2)+l*x(1))-x(8);
   16500-(58.5)*(r*x(3)-l*x(4))-x(9);
   -(58.5)*(l*x(3)+r*x(4))-x(10)];
```

2nd iteration

Voltage at train level fixed to 17500V

Downhill, NO FESS

Current from Duved: x(1) + jx(2)

Current from Östersund: x(3) + jx(4)

Current to the train: x(5) + jx(6)

Voltage of the train: x(7) + jx(8)

Active power train: x(9)

Reactive power train: Qt

Line resistance: r

Line inductance: l

```
 Qt=0;

r=0.28;

l=0.23;

 F=[16500*x(1)+16500*x(3)-x(9)-r*(km*(x(1)^2+x(2)^2)+(117 km)*(x(3)^2+x(4)^2));

     -16500*x(2)-16500*x(4)-Qt-l*(km*(x(1)^2+x(2)^2)+(117-km)*(x(3)^2+x(4)^2));

    x(7)*x(5)+x(8)*x(6)-x(9);

     x(8)*x(5)-x(7)*x(6)-Qt;

    16500-km*(r*x(1)-l*x(2))-x(7);

    -km*(r*x(2)+l*x(1))-x(8);

    16500-(117-km)*(r*x(3)-l*x(4))-x(7);

    -(117-km)*(l*x(3)+r*x(4))-x(8);

   x(7)^2+x(8)^2-17500^2];
```

Uphill, NO FESS

Current from Duved: x(1) + jx(2)

Current from Östersund: x(3) + jx(4)

Current to the train: x(5) + jx(6)

Voltage of the train: x(7) + jx(8)

Active power train: x(9)

Equivalent resistance: x(10)

Reactive power train: Qt

Line resistance: r

Line inductance: l

```
Qt=0;

r=0.28;

l=0.23;


F= [16500*x(1)+16500*x(3)-x(9)-r*(km*(x(1)^2+x(2)^2)+(117-km)*(x(3)^2+x(4)^2));

    -16500*x(2)-16500*x(4)-Qt-l*(km*(x(1)^2+x(2)^2)+(117-km)*(x(3)^2+x(4)^2));

    x(9)*x(10)-x(7)^2-x(8)^2;

    x(7)*x(5)+x(8)*x(6)-x(9);

    x(8)*x(5)-x(7)*x(6)-Qt;

    13500^2-x(7)^2-x(8)^2;

    16500-km*(r*x(1)-l*x(2))-x(7);

    -km*(r*x(2)+l*x(1))-x(8);

    16500-(117-km)*(r*x(3)-l*x(4))-x(7);

    -(117-km)*(l*x(3)+r*x(4))-x(8)];
```

3rd iteration

Downhill, FESS

Current from Duved: x(1) + jx(2)

Current from Östersund: x(3) + jx(4)

Line current between FESS and train: x(5) + jx(6)

Voltage of the train: x(7) + jx(8)

Voltage of FESS: x(9) + jx(10)

```
Pt=-3460000;

Qt=0;

Pf=-4190000;

Qf=0;

r=0.28;

l=0.23;


F=[16500*x(1)+16500*x(3)-Pt+Pf-r*(km*(x(1)^2+x(2)^2)+(58.5km)*(x(5)^2+x(6)^2)+(58.5)*(x(3)^2+x(4)^2));

   -16500*x(2)-16500*x(4)-Qt+Qf-l*(km*(x(1)^2+x(2)^2)+(58.5-km)*(x(5)^2+x(6)^2)+(58.5)*(x(3)^2+x(4)^2));

   x(7)*(x(1)+x(5))+x(8)*(x(2)+x(6))-Pt;

   x(8)*(x(1)+x(5))-x(7)*(x(6)+x(2))-Qt;

   x(9)*(x(5)-x(3))+x(10)*(x(6)-x(4))-Pf;

   x(10)*(x(5)-x(3))-x(9)*(x(6)-x(4))-Qf;

   16500-km*(r*x(1)-l*x(2))-x(7);

   -km*(r*x(2)+l*x(1))-x(8);

   16500-(58.5)*(r*x(3)-l*x(4))-x(9);

   -(58.5)*(l*x(3)+r*x(4))-x(10)];
```

Uphill, FESS

Current from Duved: x(1) + jx(2)

Current from Östersund: x(3) + jx(4)

Line current between FESS and train: x(5) + jx(6)

Voltage of the train: x(7) + jx(8)

Voltage of FESS: x(9) + jx(10)

Power train: x(11)

```
Qt=0;

Qf=0;

Pf=1340000

r=0.28;

l=0.23;


F=

[16500*x(1)+16500*x(3)-x(11)+Pf-r*(km*(x(1)^2+x(2)^2)+(58.5-km)*(x(5)^2+x(6)^2)+(58.5)*(x(3)^2+x(4)^2));

   -16500*x(2)-16500*x(4)-Qt+Qf-l*(km*(x(1)^2+x(2)^2)+(58.5-km)*(x(5)^2+x(6)^2)+(58.5)*(x(3)^2+x(4)^2));

   x(7)*(x(1)+x(5))+x(8)*(x(2)+x(6))-x(11);

   35.36*x(11)-x(7)^2-x(8)^2;

   x(8)*(x(1)+x(5))-x(7)*(x(6)+x(2))-Qt;

   x(9)*(x(5)-x(3))+x(10)*(x(6)-x(4))-Pf;

   x(10)*(x(5)-x(3))-x(9)*(x(6)-x(4))-Qf;

   16500-km*(r*x(1)-l*x(2))-x(7);

   -km*(r*x(2)+l*x(1))-x(8);

   16500-(58.5)*(r*x(3)-l*x(4))-x(9);

   -(58.5)*(l*x(3)+r*x(4))-x(10)];
```

Time between each measurement during uphill

NO FESS

20,9339	21,8019	22,58206	23,26004	23,8304	24,2959	24,665	24,95	25,165	25,3226	25,434

3MW

20,142	20,26619	20,3747	20,47	20,5539	20,6284	20,6949	20,7513	20,8059	20,8556	25,434